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Demonstration of an Automated Oil Spill Detection System

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14. ABSTRACT

Current spill detection and response strategies rely solely upon the use of human observation to visually detect the presence of a surface sheen indicative of a petroleum spill. The practice of relying upon human observers to detect spills, even when conscientiously applied, has severe shortcomings. Spills often occur at unanticipated times or places in which no one is present to see and report the event. The Spill Sentry automated oil spill monitoring/alarm sensor technology was developed to address the need for rapid reliable spill detection. The objectives of this ESTCP demonstration were to validate the newly developed automated oil spill sensor technology under real-world conditions and to promote rapid transition to DoD users by facilitating commercialization, user awareness, and regulatory acceptance. To meet these objectives, year-long field demonstrations were conducted at Puget Sound Naval Shipyard, Langley Air Force Base, Norfolk Naval Station, and Pearl Harbor Naval Station. In addition, in order to validate the system under controlled conditions and to verify performance parameters, wave-tank testing was conducted at the Ohmsett National Oil Spill Response Test Facility in Leonardo, New Jersey. The system detects petroleum contamination in aquatic systems with an upward-looking, in-water, multispectral, underwater fluorometer. The sensor continuously records hydrocarbon data via a wireless link to a base station computer. The computer serves to log, process, and display data in real time; it provides automated telephonic alarming in the event of a detected spill; and supports real-time remote data access through inter or intranet. The system met or exceeded performance objectives for spill detection, effectiveness in the presence of waves, window biofouling prevention, maintenance, ease of use, deployment (locating), spectral background interference, and oil type discrimination. The system did not meet objectives for reliability (up time) and false alarming. Lessons learned from the demonstration deployments have lead to substantial system design improvements. The total five-year life cycle cost for a four-sensor wireless Spill Sentry installation is estimated to be $105,000. The system could pay for itself by reducing the volume of petroleum unintentionally spilled into the environment by 200 gallons over its five year life. The Spill Sentry oil spill detection technology was transitioned to the private sector during the first year of the ESTCP validation effort to Applied Microsystems Ltd. (AML, Sidney, B.C.). The U.S. Navy assigned exclusive rights to manufacture and market the Spill Sentry technology to AML in exchange for an initial licensing fee and royalties on all future sales of Spill Sentry

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LIST OF ABBREVIATIONS AND ACRONYMS

AFB	Air Force Base
AML	Applied Microsystems, Ltd.
bbl	Barrel
cm	Centimeters
DoD	Department of Defense
ECAM	Environmental cost assessment model
ESTCP	Environmental Security Technology Certification Program
FCC	Federal Communication Commission
FISC	Fleet Industrial Supply Center
FM	Frequency Modulation
Ft	Feet
RMS	Root Mean Square
IP	Internet protocol
IT	Information technology
K	1000
LAN	Local area network
LC	Life cycle
ml	Milliliter
Mo	Month
MSE	Mean square error (variance)
MHz	Megahertz
NAVFAC	Naval Facilities Engineering Command
NAVSTA	Naval Station
NRDA	Natural Resource Damage Assessment
OSOT	Oil Spill On-site Team
PC	Personal Computer
POLs	Petroleum, oils, and lubricants
PPE	Personal protective equipment
PSNSY	Puget Sound Naval Shipyard
QA/QC	Quality assurance / quality control
RMS	Root mean square
RMSE	Root mean square error (standard deviation)
SSCSD	SPAWAR Systems Center, San Diego
SPAWAR	Space and Naval Warfare Systems Command
SPAWARSYSCEN	Space and Navel Warefare Systems Center
UV	Ultraviolet
VA	Virginia
Yr	Year

ACKNOWLEDGEMENTS

Sponsorship. The technology demonstration described in this final report was sponsored by the U.S. Department of Defense *Environmental Security Technology Certification Program* (ESTCP). Original development of the *Spill Sentry* automated oil spill sensing system was sponsored by Mr. Andy Del Collo of the U.S. Navy's *Pollution Prevention Ashore* program.

Participants. Some of the key participants contributing to the overall success of this project include: Bill Boucher at Puget Sound Naval Shipyard, Maureen Conners at Norfolk Naval Station, Karen Barta and Lisa Swann at Langley Air Force Base, and Cynthia Pang, Chief Robinson and the OSOT crew at Pearl Harbor. Bill Schmidt and James Lane of the Department of the Interior's Minerals Management Service were very helpful in coordinating the testing at Ohmsett. Tom Dakin, Mike Penny, and Greg Eaton of Applied Microsystems, Ltd. have been instrumental in improving upon the original Navy prototype and redesigning it for commercial applications. Gregory Anderson of SPAWARSYSCEN San Diego provided design expertise as the project lead engineer.

ABSTRACT

Current spill detection and response strategies rely solely upon the use of human observation to visually detect the presence of a surface sheen indicative of a petroleum spill. The practice of relying upon human observers to detect spills, even when conscientiously applied, has severe shortcomings. Spills often occur at unanticipated times or places in which no one is present to see and report the event. The *Spill Sentry* automated oil spill monitoring/alarm sensor technology was developed to address the need for rapid reliable spill detection. The objectives of this ESTCP demonstration were to validate the newly developed automated oil spill sensor technology under real-world conditions and to promote rapid transition to DoD users by facilitating commercialization, user awareness, and regulatory acceptance. To meet these objectives, year-long field demonstrations were conducted at Puget Sound Naval Shipyard, Langley Air Force Base, Norfolk Naval Station, and Pearl Harbor Naval Station. In addition, in order to validate the system under controlled conditions and to verify performance parameters, wave-tank testing was conducted at the Ohmsett National Oil Spill Response Test Facility in Leonardo, New Jersey. The system detects petroleum contamination in aquatic systems with an upward-looking, in-water, multispectral, underwater fluorometer. The sensor continuously records hydrocarbon data via a wireless link to a base station computer. The computer serves to log, process, and display data in real time; it provides automated telephonic alarming in the event of a detected spill; and supports real-time remote data access through inter or intranet. The system met or exceeded performance objectives for spill detection, effectiveness in the presence of waves, window biofouling prevention, maintenance, ease of use, deployment (locating), spectral background interference, and oil type discrimination. The system did not meet objectives for reliability (up time) and false alarming. Lessons learned from the demonstration deployments have lead to substantial system design improvements. The total five-year life cycle cost for a four-sensor wireless *Spill Sentry* installation is estimated to be $105,000. The system could pay for itself by reducing the volume of petroleum unintentionally spilled into the environment by 200 gallons over its five year life. The *Spill Sentry* oil spill detection technology was transitioned to the private sector during the first year of the ESTCP validation effort to Applied Microsystems Ltd. (AML, Sidney, B.C.). The U.S. Navy assigned exclusive rights to manufacture and market the Spill Sentry technology to AML in exchange for an initial licensing fee and royalties on all future sales of *Spill Sentry* systems worldwide. In addition, the U.S. federal government receives discounted pricing for *Spill Sentry* systems purchased for government use and activities. AML has sold *Spill Sentry* systems worldwide and continues to manufacture and market the systems.

1.0 INTRODUCTION

1.1 BACKGROUND

The mandatory cleanup of accidental releases of petroleum into the environment costs the Department of Defense (DoD) millions of dollars annually. DoD agencies are responsible for the cleanup of thousands of barrels of petroleum hydrocarbons (POL) spilled into the marine environment each year. The total volume of accidental POL releases at Navy facilities alone has exceeded 3.4 million gallons over the past decade. Estimates of the associated economic costs, which include cleanup, disposal and lost product; and fines range from a low of $2,000/bbl to as high as $18,000/bbl. Other, non-economic costs associated with major spill occurrences include irreversible harm to ecologically sensitive areas as well as damage to local community relations arising from a perception of negligent environmental stewardship within the DoD.

Current spill detection and response strategies rely solely upon the use of human observation to visually detect the presence of a surface sheen indicative of a petroleum spill. Once an oily sheen is spotted, a response team is alerted to contend with the spill. The response team will first seek to isolate and stop the source if a leak is still occurring, then use any combination of skimmers, absorbents and booms to contain and remove the spilled material. Early identification of a leak or spill, enabling responders to take immediate corrective action is an important means of preventing large volume releases and reducing the associated environmental damage and economic cost. Early spill identification can only be achieved through diligent continuous monitoring.

The practice of relying upon human observers to detect spills, even when conscientiously applied, has severe shortcomings. Spills often occur at unanticipated times or places in which no one is present to see and report the event. It is not uncommon for pipeline and container leaks to go undetected for many hours and sometimes days, allowing small leaks to accumulate into large spills before corrective action is applied. Weekends and holidays are particularly susceptible to large spill occurrences as reduced manning and an often unreliable watch increases the likelihood that a spill will go undetected for extended periods of time. The inability to reliably depend upon visual observation also impacts port operations as commanders seek to minimize spill risk exposure. For example, because visual observation is particularly ineffective at night, operations involving the transfer of fuel or oily waste (bilge pumping) must generally be restricted to daylight hours. This frequently causes an early morning backlog in the demand for port services and results in otherwise avoidable operational delays.

The *Spill Sentry* automated oil spill monitoring/alarm sensor technology was developed to address the need for rapid reliable spill detection. Developed under Navy/Naval Facilities Engineering Command (NAVFAC) 6.4 funding, *Spill Sentry* provides continuous, around-the-clock, automated monitoring of POL contaminants in and on water. The system is intended to eliminate or minimize the need for human visual observation in detecting oil spills on water. It operates both day and night and under all weather conditions, promoting rapid, reliable notification and facilitating timely corrective responses. Cleanup costs, fees and environmental damage can be significantly reduced because of the resulting spill minimization.

1.2 OBJECTIVES OF THE DEMONSTRATION

The objectives of this demonstration were to validate the newly developed automated oil spill sensor technology under real-world conditions and to promote rapid transition to DoD users by facilitating commercialization, user awareness, and regulatory acceptance. To meet these objectives, year-long field demonstrations were conducted at Puget Sound Naval Shipyard, Langley Air Force Base, Norfolk Naval Station and Pearl Harbor Naval Station. In addition, in order to validate the system under controlled conditions and to verify performance parameters, wave-tank testing was conducted at the Ohmsett National Oil Spill Response Test Facility in Leonardo, New Jersey. Ultimately, the final intended goal in demonstrating the effectiveness of utilizing an automated oil spill monitoring system is to provide users with the means to eliminate the need for 100% reliance on human visual observation to detect oil spills.

1.3 REGULATORY DRIVERS

U.S. Army, Navy and Air Force facilities are required to comply with Federal, state and local legislation relating to the control of marine and aquatic oil pollution. Federal legislation[1] requires reporting and cleanup of any spill large enough to cause a surface sheen on the water. In California, the Lempert-Keene-Seastrand Oil Spill Prevention and Response Act of 1990[2] requires the implementation of an oil pollution monitoring program at all marine oil transfer facilities in the state, yet no service branch to date has implemented a compliant program.

Demonstration of the automated oil spill monitoring/detection system also directly addresses high priority U.S Navy / Tri-Service needs as documented in the ESTRG Requirement: *(ID number 2.V.1.x) Oil Spill Detection, Minimization, and Recovery Technology*

1.4 STAKEHOLDER/END USER ISSUES

The *Spill Sentry* technology demonstration sought to establish user confidence in the new oil spill detection technology. This was especially important as automated spill detection represents a completely new approach to pier-side monitoring. End-users have expressed concern over issues including the potential for generating false positives, the importance of data security, overall ease of use, low cost, durability including the ability to withstand severe storms, and effectiveness in detecting oil. Information and network security also represents a broader user concern when linking the oil spill sensors' real-time web-based data capability to local networks.

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[1] Clean Water Act (33 U.S.C. 1251), Oil Pollution Act of 1990 (33 U.S.C. 2701 et. seq.), Oil Pollution Prevention Regulations for Marine Oil Transfer Facilities (33 CFR 154), Discharge of Oil (40 CFR 110), Pollution Prevention Act of 1990, and Oil Spill Prevention Control and Counter Measures Planning Manual (NFESC 7-03), OPNAVINST 5090.1B.

[2] California Government Code and Public Resource Code, collectively referred to as the *Lempert-Keene-Seastrand Oil Spill Prevention and Response Act*. California Government Code: *Chapter 7.4, Oil Spill Response and Contingency Planning Articles 1-10*; Public Resource Code: *Division 7.8 Oil Spill Prevention and Response, Sections 8750-8760*

2.0 TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY DEVELOPMENT AND APPLICATION

The technology was originally developed by the U.S. Navy at Space and Navel Warefare Systems Center (SPAWARSYSCEN) San Diego. Development of the automated oil spill detection system began in 1995 with the first prototypes being tested in 1997. Work to incorporate engineering refinements and improvements continue into the present. The basic technology is protected by U.S Patent US05929453, *Underwater Multispectral Fluorometer,* issued in January 2000. The Navy has licensed exclusive worldwide rights to commercialize the technology to *Applied Microsystems, Ltd*. (AML) of Sidney, B.C., Canada. As of June 2000, AML manufactures and markets a product under the trade name *Spill Sentry. Spill Sentry* is closely based upon the original Navy design.

2.1.1 System Description

The system detects petroleum contamination in aquatic systems with a an upward-looking, multispectral, underwater fluorometer. It is a point sensor, measuring petroleum *in situ*, that can be deployed in arrays to provide area coverage. The sensor's overall hardware design is intended to be rugged and inexpensive to manufacture. The sensor is shown in Figure 2.1. Each sensor is 20 inches tall, with a float diameter of 18 inches. The housing is primarily constructed of polyvinyl chloride (PVC) with a polyethylene float. It uses the light of a pulsed xenon flash lamp to induce fluorescence in the aromatic components of free phase, dissolved phase and emulsified petroleum hydrocarbon contamination in and on the water column. The lamp's optical output is collimated by an f/1 lens then spectrally split by a dichroic beam splitter into visible and ultraviolet (UV) (< 315nm) components that are used to excite fluorescence. The spectral separation is further enhanced by use of a custom made optical high (frequency) pass filter to achieve an extinction ratio in excess of 10^{-6}. The UV excitation light is reflected by a second dichroic beam splitter through an optical window out into the water column. The resulting fluorescence emission is collected back through the same window (180^{o}) and directed through a series of dichroic filters for spectral separation before being measured by multiple photodetectors. A photodiode is used to monitor the UV-visible waste beam from the first beam splitter to normalize the fluorescence emission signal for pulse-to-pulse variations in lamp intensity. The output of this photodiode also serves to trigger the detection electronics. The lamp source and analog-to-digital conversion of the photodetector output is managed by an embedded microprocessor located in the underwater housing. Data and power are transferred in one of two ways: either through a hard-wired umbilical or via a wireless data link incorporating solar power for complete autonomy.[3]

Fluorescence provides an extremely sensitive method allowing for accurate quantification of trace levels of hydrocarbons. The system can in principle detect all natural petroleum-based fuels and oils but does not respond to other types of oil or grease. The lower detection limit has been

[3] A description of the sensor system design appears in*: Multispectral fluorometric sensor for in-situ detection of marine petroleum spills*, John Andrews and Stephen Lieberman, Oil and Hydrocarbon Spills, R. Garcia-Martinez and C.A. Brevia, Eds., pp 291-301; Computational Mechanics Publications, Southampton, UK, 1998

tested below the U.S. Coast Guard defined threshold for an oil spill, i.e. the appearance of visible sheen. The absolute limit of detection is unknown.

Multichannel spectral analysis allows discrimination between various classes of hydrocarbons and minimizes interference due to non-hydrocarbon fluorescence. Background fluorescence due to the presence of POLs is assimilated into a baseline measurement to enable distinction between ambient "normal" POL levels and an actual spill. The sensor incorporates a unique, one-window optical design that makes use of the ultraviolet light energy generated by the fluorescence excitation source to prevent biofouling of the optical window thereby enabling the sensors to remain underwater for indefinite periods of time. The sensor continuously records hydrocarbon data via a wireless link to a base station computer. The computer serves to log, process and display data in real time; it provides automated telephonic alarming in the event of a detected spill; and supports real-time remote data access through inter-or intranet.

2.2 PREVIOUS TESTING OF THE TECHNOLOGY

Prior to the ESTCP effort described in this report, early prototypes of the system were tested in limited series of studies conducted at the Ohmsett National Oil Response Test Facility August 1997. Ultraviolet prevention of biofouling had been demonstrated for periods up to two months in San Diego Harbor between 1997 and 1998. The results of early testing are published in *Oil and Hydrocarbon Spills, Modeling, Analysis and Control*, R. Garcia-Martinez and C. A. Brebbia Eds., pages 291-301, Computational Mechanics Publications, 1998.

2.3 FACTORS AFFECTING COST AND PERFORMANCE

The factors affecting the cost of deploying the technology include expenses associated with the initial system installation and system maintenance over its anticipated lifetime. Installation or start-up costs depend upon several variables including whether the newly installed sensors are hard-wired to shore power and network lines or, alternatively, installed as stand alone wireless systems using FM transmission and solar power. Wireless systems are somewhat more costly to produce, however hard-wired systems may require costly infrastructure modifications to support sensor deployment. Maintenance costs are expected to be minimal, limited to periodic cleaning of the underwater housing and annual replacement of the flashlamp and internal battery.

Performance may be affected by unanticipated sensor fouling, difficulties in maintaining a continuous data link, poor judgment in sensor placement, or algorithm failure leading to the occurrence of frequent false alarms.

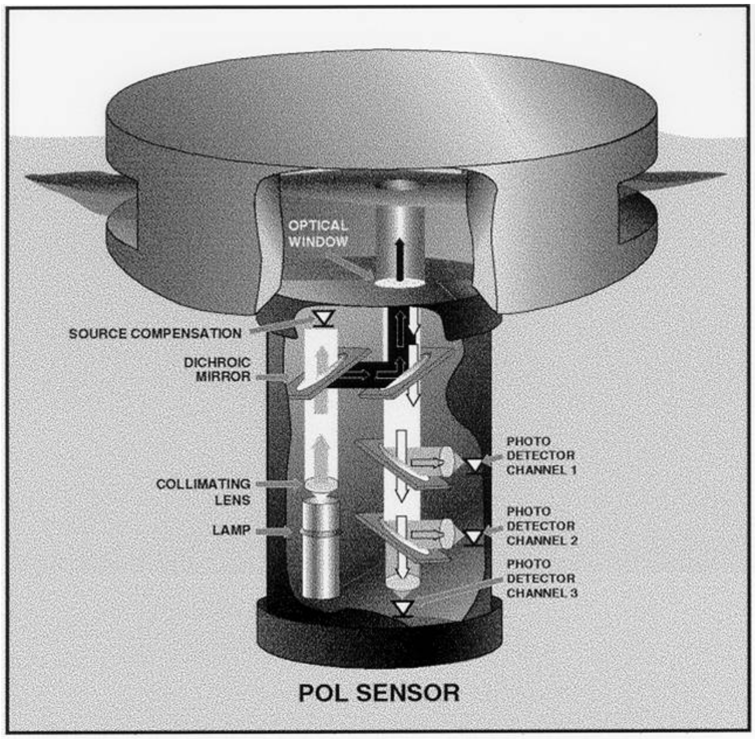

Figure 2.1 The Oil Spill Sensor.

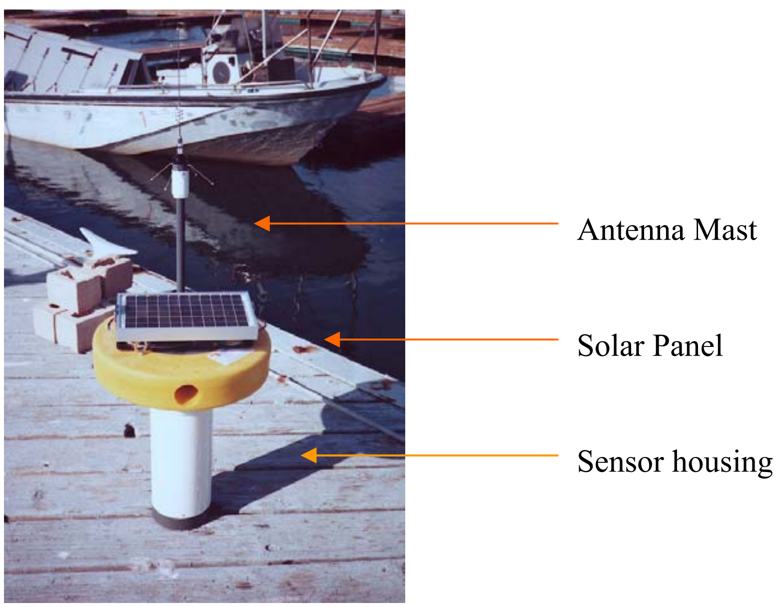

Figure 2.2 Wireless *Spill Sentry* Sensor.

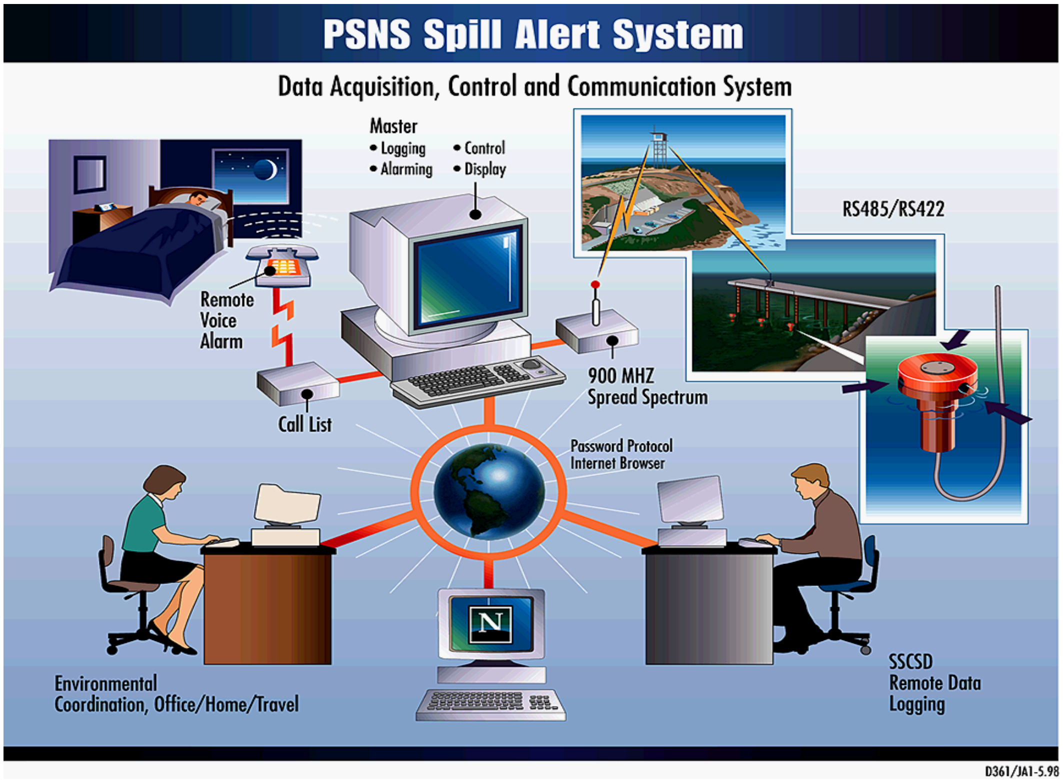

Figure 2.3 The Spill Alert System.

2.4 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The sensor system offers the following advantages:

1. Remote automated detection of petroleum hydrocarbons from below the water surface.
   a. This allows dissolved phase and emulsified hydrocarbons to be measured directly in the water column.
   b. By placing the sensor near the surface, floating petroleum can simultaneously be detected from below the oil-water interface. The sensor buoy maintains the sensor window at a distance of two inches from the surface at all times independent of tidal movement or limited wave action. The sensors may be kept in place by an anchor or by simply being tied-off to a fixed object. However the sensors must be moored in such a way that they do not interfere with ship traffic.
   c. Underwater deployment also provides an inherently safe means of delivering excitation energy to the sample (water). With an above water sensor, there would exist the potential to be into direct contact with explosive fuel vapors during a spill. High voltage electronics that trigger the excitation source (lamp) would have to be isolated in an explosion-proof housing for safety. This problem is avoided through underwater placement.
2. The optical window has been designed to remain free of biological fouling. By using a 180^0 optical geometry for the fluorescence excitation/emission-collection, the sensor requires the use of a single optical window. This may be contrasted with the more typical

> 90^0 geometry that requires the use of two windows. The advantage of a single window design is that the ultraviolet excitation light passing through the window prevents biological growth from forming. Thus, the sensor can remain underwater for indefinite periods of time. The underwater deployment duration is not limited by window fouling, which typically limits the deployment duration for other underwater optical instruments.

One limitation of the system is that each sensor monitors a single point on the water surface directly above itself. Area coverage per sensor is entirely dependent upon wind and current forces that tend to spread spills. In other words, the spill must come to the sensor. The specific number of sensors needed to cover a given area will therefore vary widely; a rough starting point may be 200 feet between sensors for continuous area coverage. Enhanced area coverage can be attained only through the use of multiple sensor arrays.

Another limitation, the system performance can be severely degraded in turbid water. The optically based sensors are only as effective as their ability to "see" into and through water. The sensor will no longer be effective if optical transmission through the water column drops to zero.

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3.0 DEMONSTRATION DESIGN

3.1 PERFORMANCE OBJECTIVES

The primary performance objectives for the *Spill Sentry* oil spill detection system are summarized below in Table 3.1. The first objective was for the optical sensor to successfully detect the presence of a reportable spill with 95% effectiveness or better. In other words, the sensor should be able to detect 95% of all oil spills regardless of circumstances. The next objective was for a physically robust and reliable system, one that is up and properly functioning a minimum of 99% of the time. This is a rigorous requirement but necessary for an alarm system that users can confidently rely upon. Low maintenance was another objective, with the targeted level of scheduled and unscheduled maintenance being less than 2 man-hours labor required per sensor per month. False alarms are a major concern of all users and were addressed by the next objective; the performance target for this objective was less than one per month. Finally, ease of use was the last objective; it was assessed based upon subjective user feedback.

In addition to the primary performance objectives, several secondary performance objectives to be evaluated were specified. These included a background spectral interference of no more then 30% total signal intensity at any time, optical windows remaining free of bioaccumulation for at least 180 consecutive days, the ability to detect oil in up to one-foot seas, the ability to position sensors with zero impact to operations, and the ability to spectrally discriminate between light and heavy fuel products in 90% of cases. The secondary performance objectives are summarized in Table 3.2. Actual performance results are discussed in Section 4.

Table 3.1 Primary Performance Objectives

Type of Performance Objective	Primary Performance Criteria	Expected Performance Metric
Quantitative	1. Detect spills/sheen	Alarm 95% of spills
	2. Reliability	99% system up-time
	3. Maintenance	< 2 man-hours/ sensor/ month
	4. Minimize false alarms	< 1/month
Qualitative	1. Ease of Use	User satisfied

Table 3.2 Secondary Performance Objectives

Secondary Performance Objective	Performance Criteria	Performance Metric
Background Spectral Interference	Percent of discrete signal intensity attributed to factors other than the presence of POL	Spectral interference never contributing to more than 30% of total signal intensity
Window fouling	Duration of time window remains free of obscuring matter	Optical sensor window remains free of biofouling > 6 months continuous use.
Rough weather	Effectiveness in choppy seas or foul weather	Maintain effectiveness in up to 1-foot harbor chop
Locating	Ease of deploying sensors in critical areas	Ability to deploy without interference with port operations Ability to deploy with minimal infrastructure (pier) modifications
Type discrimination	Ability to discriminate between oil/fuel products	Ability to spectrally discriminate heavy vs light POL products with 90% accuracy (correct classification of *heavy* or *light* in 9/10 cases)

3.2 SELECTING TEST SITES/FACILITIES

Demonstration sites were selected on the following basis: support of the hosting facility, availability of adequate infrastructure, history of or potential for frequent of spill occurrences, and environmental or operational diversity. The spill frequency criterion was more heavily weighted due to the relative infrequency (a few times/year) of large (>1000gal) spills. Site selection was intended to maximize the probability that at least one large spill would occur during the finite time period of the demonstration.

Comtrolled testing was performed at the Department of the Interior's Ohmsett test facility in New Jersey. Ohmsett provides a large wave tank dedicated to the test and evaluation of oil spill detection and response equipment. It enables key quantitative tests to be performed in a controlled environment without having to wait for a random spill event as at the demonstration sites.

3.3 TEST SITE CHARACTERISTICS AND HISTORY

Along with Ohmsett, four active DoD facilities were selected to host concurrent demonstrations. At each facility, sensor locations were determined through consultation with local responders and authorities. A brief description of each follows.

3.3.1 Langley Air Force Base

Langley Air Force Base, Va., is among the oldest continuously active air bases in the United States. The facility is home to the 1st Fighter Wing flying the F-15 Eagle. Covering 2,900 acres, Langley Air Force Base is located on the Tidewater Peninsula, almost to North Carolina. The peninsula is situated between Norfolk, Virginia Beach and Colonial Williamsburg. Langley is located in the city of Hampton, which is near Newport News, Poquoson, York County and James City County**.** An aerial view of Langley AFB is show in Figure 3.1 along with a map in Figure 3.2.

A single sensor was placed along the lone fuel pier at Langley. The spill history of the site is unknown as the facility does not keep written records of spill events. The site was primarily selected because the demonstration could be logistically supported at very small additional cost to the concurrent and nearby Norfolk demonstration, and because it provides an opportunity to test the system a) in an estuary river, and b) in an Air Force operational environment. The sensor positioning did not hinder ship movement or fueling operations.

3.3.2 Naval Station Norfolk

Naval Station Norfolk occupies about 3,400 acres of Hampton Roads real estate in a peninsula known as Sewells Point. It is the world's largest Naval Station. The Naval Station is homeport to aircraft carriers, cruisers, destroyers, large amphibious ships, submarines, a variety of supply and logistics ships, C-2, C-9, C-12 and E-2 fixed wing aircraft, and H-3, H-46, H-53, and H-60 helicopters. Norfolk, with its 14 piers, is homeport to 78 ships. Port Services controls more than 3,100 ships' movements annually as they arrive and depart their berths. Port facilities extend more than four miles along the waterfront and include some seven miles of pier and wharf space.

Figure 3.1 Langley Air Force Base, Aerial View.

Figure 3.2 Map of Area Surrounding Langley Air Force Base.

Three wireless sensors were installed at Norfolk. Two sensors were located along the waterfront piers with an additional sensor to be located at the Bousche Creek Outfall. The site was selected because its history of frequent large spills (>1,000 gallons) which have occurred at a rate of 2-3 per year over the past decade. The sensors were located so that they will not interfere with ship movement or waterfront operations. The base station was established at the Port Operations center located near the waterfront. The sensor locations are graphically depicted in Figure 3.5.

Figure 3.3 Naval Station Norfolk, Aerial View.

Figure 3.4 Map of Area Near Norfolk Naval Station.

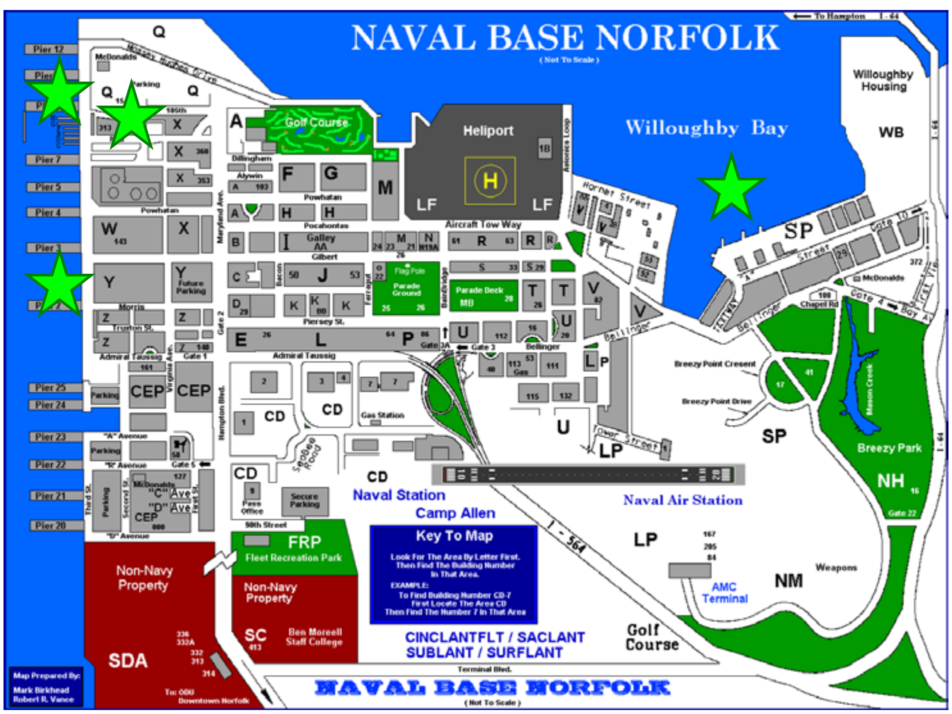


Figure 3.5 Location of Spill Sentry sensors at NAVSTA Norfolk. (Sensor and base-station locations are shown as green stars).

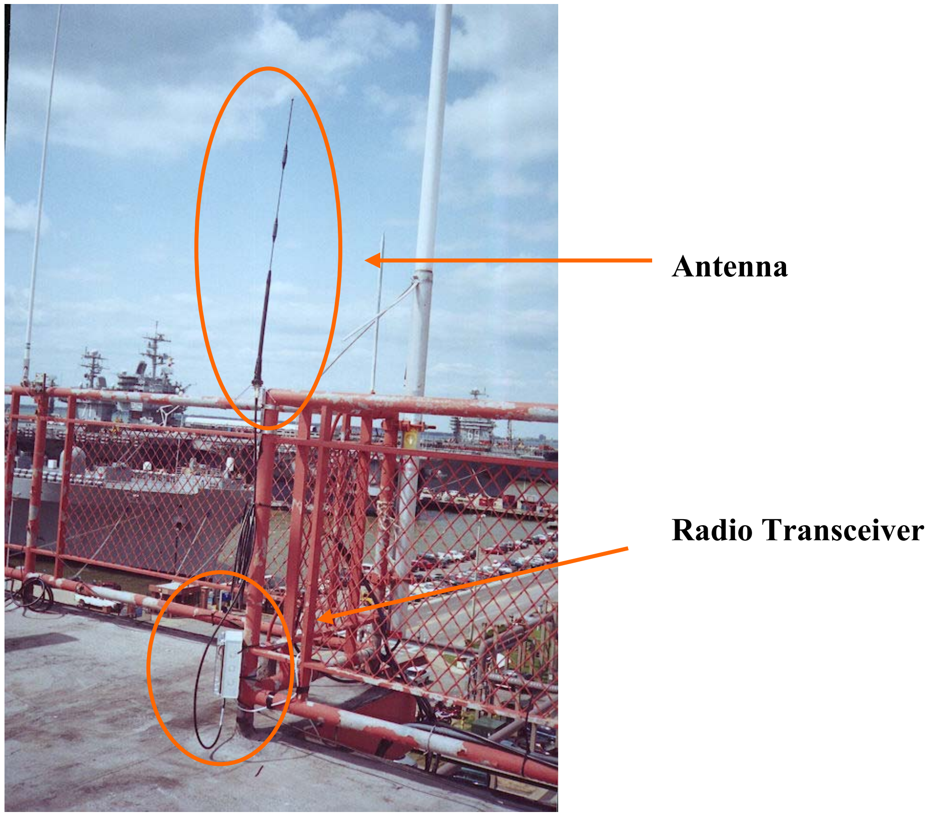


Figure 3.6 Base-station Radio and Antenna Mounted atop the Port Operations Building.

3.3.3 Puget Sound Naval Shipyard

Puget Sound Naval Shipyard was originally established in 1891 as a Naval Station and was designated Navy Yard Puget Sound in 1901. Approximately 30% of the Shipyard's current workload involves inactivation, reactor compartment disposal, and recycling of ships. Puget Sound Naval Shipyard is the Pacific Northwest's largest Naval shore facility and one of Washington State's largest industrial installations. It is also the largest shipyard on the West Coast, employing approximately 7,700 people.

Figure 3.7 Aerial View of Puget Sound Naval Shipyard.

Four hard-wired sensors were installed at the shipyard. The sensors were all installed along Pier B. The site was primarily selected because of its relatively frequent occurrence of large spills (>1/year). The sensors did not interfere with ship movement or pier side operations. The hard-wired sensors each communicated directly with a radio transceiver located near the pier. Data was then transmitted over a wireless data link to the base station computer located approximately 500 meters away on the third floor of the FISC building.

3.3.4 Naval Station Pearl Harbor

Naval Station Pearl Harbor supports 50 home ported fleet units and 24 submarines. The station currently occupies and maintains 1,107 acres of land throughout the Pearl Harbor complex, ranging from Waipio Peninsula to Bishop Point and including Ford Island. Operating the Navy's busiest harbor, Naval Station Pearl annually completes 65,000 boat runs and transports 2.4 million passengers and 200,000 vehicles to and from Ford Island and other harbor locations. Navy-manned USS Arizona tour boats transport nearly 2 million visitors to the memorial each year.

Four wireless sensors were installed at Pearl Harbor. The sensors were located near the Arizona Memorial, and at piers H2/3, M2/3, and B17. The base station was located at the Oil Spill On-Site Team (OSOT) oil spill response center located on Ford Island. The site was primarily selected because its history of relatively frequent large spills (> 1/year) and for the opportunity to test the sensors in a diverse biofouling environment. The sensors positioning did not interfere with ship traffic or pier side operations.

Arizona Memorial

Pier H2

Pier B17

Pier M2

Figure 3.8 *Spill Sentry* Sensor Locations at Pearl Harbor.

Mast and antenna

Figure 3.9 Base-station Mast and Antenna Mounted on the OSOT Building, Ford Island.

(a) (b)

Figure 3.10 Radio Transceiver (a) and Antenna Mast (b) on OSOT Building.

3.3.5 Ohmsett Test Facility

Ohmsett is located at the Naval Weapons Station Earle Waterfront in scenic Leonardo, New Jersey (approximately one hour south of New York City). The large, outdoor, aboveground concrete test tank measures 203 m long by 20 m wide by 3.4 m deep. The tank is filled with 2.6 million gallons of crystal clear saltwater. The Ohmsett test tank allows testing of full-scale equipment. The tank's wave generator creates realistic sea environments, while state-of-the-art data collection and video systems record test results. Ohmsett’s features and capabilities include:

- A main towing bridge capable of towing test equipment at speeds up to 6.5 knots;
- An auxiliary bridge oil recovery system to quantify skimmer recovery rates;
- A wave generator capable of simulating regular waves up to one meter in height, as well as a simulated harbor chop;
- A movable, wave-damping artificial beach;
- An oil distribution and recovery system that can handle heavy, viscous oils and emulsions;
- A control tower with a fully-computerized 32-channel data collection system as well as above-sand below-water video;
- A centrifuge system to recover and recycle test oil;
- Blending tanks with a water and oil distribution system to produce custom oil/water emulsions for testing;
- A filtration and oil/water separator system;
- An electrolytic chlorinator to control biological activity;
- Permanent and mobile storage tanks that can hold over 227,000 liters of test fluids;
- A vacuum bridge to clean the bottom of the tank; and staging and shop area for special fabrication.

Through a variety of mechanical, electrical and chemical systems at Ohmsett, the following test parameters can be controlled or measured:

- Sea state (wave height, length and period);
- Meteorological data;
- Water temperature and salinity;
- Volume of oil encountered and recovered by test equipment or protocol;
- Oil-water ratios;
- Physical characteristics of experimental oil; and behavior of treated oils.

Figure 3.11 Ohmsett Test Facility.

3.4 PRESENT OPERATIONS

Present practice relies on human visual observation to identify a spill. Immediately after a spill is reported a local response team typically dispatches a crew to investigate whether the ship or (or reporting activity) needs assistance with cleanup or containment. If necessary, additional personnel are deployed to the scene. The key process, i.e. the one which *Spill Sentry* has been developed to automate and improve, is the initial spill identification procedure.

3.5 PRE-DEMONSTRATION TESTING AND ANALYSIS

No testing or analysis of current procedures was performed prior to the demonstrations. Statistical analysis of when a spill occurs vs. when it's reported has not been specifically studied for current practices. However, anecdotal evidence provided by Navy responders indicated that the range of response times currently varies from minutes to days.

3.6 TESTING AND EVALUATION PLAN

3.6.1 Demonstration Set-Up and Start-Up

The installed equipment consists of floating *Spill Sentry* oil-spill sensor(s), a data-logging base-station computer/web-server, and a wireless spread spectrum FM connection between the base-station and sensors. The sensors were moored at the deployment location; either tied directly to the pier structure or an anchor. The base-station required a LAN connection to support Internet capabilities or, as an alternative, a dial-up connection through a local phone line. The base-station also required a separate telephone connection to support telephonic alarming. The wireless data link operates at 900 MHz, a frequency and power that does not require FCC licensing; and, as it frequency-hops, it does not interfere with any wireless local transmissions. Repeaters or special directional antennas were not used. The specific installation configurations are summarized in Table 3.3.

Table 3.3 *Spill Sentry* System Configuration by Site

Site	Number of Sensors	Link	Power	Antenna	Data Access
Norfolk	3	Wireless	Solar	24" omni-directional whip	Dial-up
Langley	1	Wireless	Solar	6" whip	Dial-up
Pearl	4	Wireless	Solar	24" omni-directional whip & 20' mast	Dial-up
Puget Sound	4	Wired & Wireless	Hard-wired	6" whip	Web server
Ohmsett	2	Wireless	Solar	6" whip	Direct to PC

Window fouling was measures by periodically visual inspection. The inspection frequency was every 60 days. A mesh screen was later installed around some sensors' entrance ports to prevent physical fouling with trash, seaweed, etc.

3.6.2 Period of Operation

The facility demonstrations were conducted more or less concurrently, lasting for a period of 15 months from September 2000 to December 2001. The Ohmsett testing was conducted during May 2001. Initially planned for August 2000, technical difficulties with the Ohmsett tank necessitated a postponement until the following May.

3.6.3 Operating Parameters of the Technology

The systems are intended to operate continuously with minimal user intervention. A three-sensor wireless system was installed at both Naval Station Norfolk and Pearl Harbor; four hard-wired sensors were demonstrated at Puget Sound; and a one-sensor based wireless system was deployed at Langley Air Force Base. There is no required minimum distance between installed sensors. The maximum distance is limited only by data communication methods, i.e. up to several miles using a 2 watt FM radio. The user/operator labor requirement is limited to sensor placement assistance, responding to sensor alarms, and occasional (monthly) monitoring of the sensors to ensure they are still in place and functioning.

3.6.4 Experimental Design

The Ohmsett tests focused on sensor performance. The tests were designed to evaluate the sensor response to a variety of fuels to include at a minimum gasoline, diesel fuel, and lube oil. Each individual test involved recording the multichannel sensor response to a petroleum product under sea state conditions ranging from quiescent to chaotic wave motion up to two feet in height. The tests served to confirm that the sensors do respond to petroleum, that the sensors can perform in the presence of harbor chop, and that surface motion, sunlight, etc. do not cause a false response.

The demonstrations served to evaluate the performance of the entire system over time. This includes subjective evaluation of sensor positioning, wireless communication, and maintenance, survivability, fouling and any other, possibly unknown, effects or parameters.

The exact locations and specific distance between installed sensors at each demonstration site was decided through consultation with local prevention and response personnel. Sensors may be placed as close as 100 feet apart to provide high spatial resolution within the covered area or placed as far apart as several miles for extended coverage. A relatively closely spaced array was used at Puget Sound Naval Shipyard (100-500 feet between sensors). Relatively widespread arrays (0.5-5 miles apart) were used at Norfolk and Pearl Harbor. The Langley demonstration utilized a single sensor.

Once the sensors are deployed, the three operating parameters that may be varied are: the frequency of and interval between flashlamp discharges (measurements), and the signal threshold used for alarming. The tested range for the flashlamp was 1-5 minute intervals and 5-30 Hz frequencies. The alarm threshold was set in proportion to background oil levels; it was specific to each sensor location and could only be determined through empirical methods. The corresponding POL concentration cannot be predicted *a priori*. The alarm threshold setting accounts for any persistent dissolved background POLs that affect the baseline signal.

Should a sensor itself become externally contaminated with petroleum from a spill, it can be readily cleaned by a number of means including: the use of adsorbent wipes, high-pressure steam or simply with a surfactant and water.

Changing the flashlamp frequency and/or interval between flashes affects: a) the signal through averaging, b) window fouling because of the varying ultraviolet dosage, and c) maintenance

costs because of the limited flashlamp lifetime. Experience gained at each location throughout the demonstrations was used to optimize the balance between sensitivity (signal) and biocidal capacity, both of which improve with *increasing* flash frequency, and maintenance costs which improve with *reduced* flash frequency. An ideal balance is one that maintains sufficient sensitivity to detect a visible sheen and prevents window biofouling indefinitely while minimizing the lamp consumption rate.

The alarm threshold (or setpoint) is the sensor signal level, derived from the presence of oil, at which the base station will go into an alarm status and begin telephonic notification of responding authorities that a spill has occurred. If set too low, annoying false alarms will result; if set too high, the system may fail to identify an actual spill. The approach to threshold setting during the demonstrations was to continuously compute the mean and variance of the real-time oil signal level and then set the alarm threshold at a fixed number of standard deviations above the mean signal. Past experience has indicated that the sensor signal (amount of oil present) is normally distributed over time, hence this parametrical statistic approach to threshold setting can be associated with probability of a spill occurrence. For example, a signal-level two standard deviations above the mean indicates a 95% likelihood that a spill has occurred. An example histogram of background signal intensities is shown in Figure 3.12. At each site the threshold was initially set at two standard deviations above the mean signal level and adjusted as needed to comply with user-directed response objectives.

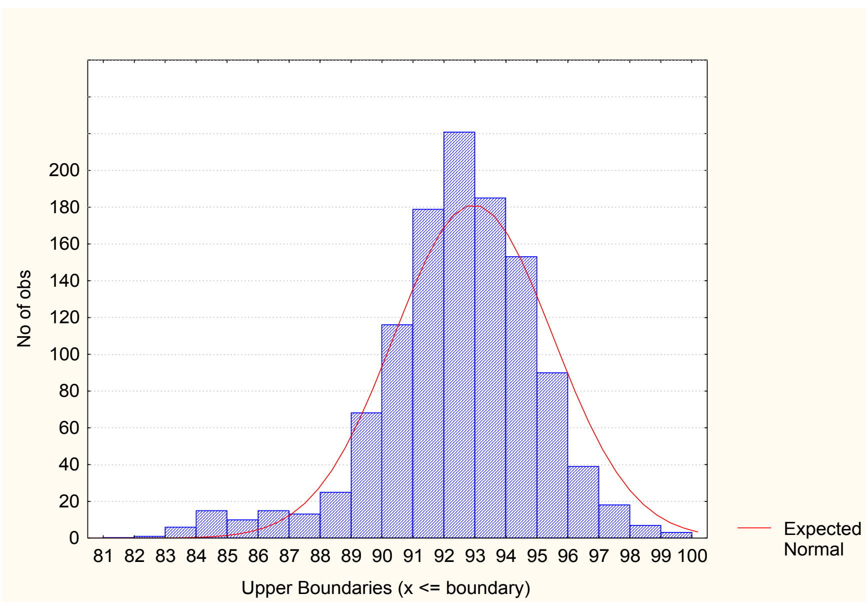


Figure 3.12 Statistical Distribution of Signal Intensities.

3.6.5 Demobilization

Upon completion of the demonstrations, the original plan called for all equipment to be recovered and returned to SPAWAR San Diego. At the discretion of the Principal Investigators, and with approval of Site-Lead, systems have been left in place at Pearl Harbor and PSNS to continue service.

4.0 PERFORMANCE ASSESSMENT

4.1 PERFORMANCE CRITERIA

The general performance criteria used to evaluate system performance are tabulated below in Table 4.1.

Table 4.1 Primary Performance Objectives with Results

Type of Performance Objective	Primary Performance Criteria	Expected Performance Metric	Actual Performance Objective Met?
Quantitative	1. Detect spills/sheen	Alarm 95% of spills	Yes
	2. Reliability	99% system up-time	No
	3. Maintenance	< 2 man-hours/ sensor/ month	Yes
	4. Minimize false alarms	< 1/month	No
Qualitative	1. Ease of Use	User satisfied	Yes

Table 4.2 Secondary Performance Objectives with results

Secondary Performance Objective	Performance Criteria	Performance Metric	Objective Met?
Background Spectral Interference	Percent of discrete signal intensity attributed to factors other than the presence of POL.	Spectral interference never contributing to more than 30% of total signal intensity.	
Window fouling	Duration of time window remains free of obscuring matter	Optical sensor window remains free of biofouling > 6 months continuous use.	Yes
Rough weather	Effectiveness in choppy seas or foul weather	Maintain effectiveness in up to 1-foot harbor chop	Yes
Locating	Ease of deploying sensors in critical areas	Ability to deploy without interference with port operations Ability to deploy with minimal infrastructure (pier) modifications	Yes
Type discrimination	Ability to discriminate between oil/fuel products	Ability to spectrally discriminate heavy vs light POL products with 90% accuracy (correct classification of *heavy* or *light* in 9/10 cases).	Inconclusive

4.2 PERFORMANCE CONFIRMATION METHODS

Expected performance and confirmation methods are tabulated below in Table 4.3. The data quality assurance / quality control strategy is outlined in Appendix E of the Demonstration Test Plan. Sensor performance was evaluated at the Ohmsett facility during a series of controlled experiments. Overall system performance was evaluated during the site demonstrations.

Table 4.3 Expected Performance and Confirmation Methods

Performance Criteria	Expected Performance	Performance Confirmation Method
PRIMARY CRITERIA (Quantitative Performance Objectives)		
Oil detection	- Detect visible sheen always - Detect user defined spill 95% of the time	User (OSOT) observation User (OSOT) observation after responding to alarms
False alarms	< 1 / month	User (OSOT) feedback
Reliability	99% system up-time	Observation during site demonstration Analysis of data time-series
Maintenance	< 2 man-hrs/sensor/month	User feedback Observation during site-demonstrations
SECONDARY CRITERIA (Qualititative Performance Objectives)		
Background Spectral Interference	Spectral interference never contributing to more than 30% of total signal intensity.	Observation during site demonstrations Ohmsett testing
Ease of Use	100% of end users satisfied with ease of use	End user interview
Window fouling	Optical sensor window remains free of biofouling > 6 months continuous use.	Observation during site-demos
Rough weather	Maintain effectiveness in up to 1-foot harbor chop	Ohmsett testing User observation Time series sensor data correlated to weather
Locating	Ability to deploy without interference with port operations Ability to deploy with minimal infrastructure (pier) modifications	User feedback User feedback, installation team feedback
Oil/Fuel type discrimination	Ability to spectrally discriminate heavy vs light POL products with 90% accuracy (correct classification of *heavy* or *light* in 9/10 cases).	Ohmsett testing Controlled observation (examining sensor response to known fuel/oil standards)

4.3 DATA ANALYSIS, INTERPRETATION AND EVALUATION

4.3.1 Controlled Testing

Tests were conducted at the Ohmsett facility to evaluate the *Spill Sentry* sensor's :

- Ability to detect various types of oil including: gasoline, diesel fuel and lube oil
- Ability to spectrally distinguish between different oil products
- Effectiveness in choppy water (rough weather)
- Effect of surface motion and ambient light on false alarms

Ohmsett performance testing was initially conducted at the Ohmsett facility in September 2000. Unfortunately the test tank contained residual oil slicks and tar globules from *in-situ* burn tests performed the previous week. The presence of significant amounts of oil made it impossible to test the sensor's detection ability as the background oil levels in the tank were simply too high, having exceeded the dynamic range of the sensor. After consulting with the Ohmsett officials, it was decided to reschedule the sensor tests until the following spring, as soon as the facility reopened after its annual winter closure. A second trip to Ohmsett in May 2001 was much more successful in generating performance data as the tank water was in pristine condition. The majority of the Ohmsett data presented is from the May testing. The testing took place over a one week period.

The primary data collected during the Ohmsett tests were the sensor response at each of the three optical channels. The response was used to determine the sensor's ability to detect oil using the following detection criterion: to detect oil on water, the signal increase due to detected oil must be greater 3.0 times the background Root Mean Square (RMS) variation in at least one optical channel. The sensor's ability to spectrally distinguish between different petroleum products was determined by evaluating the ratios or differences in the measured response of each channel. The sensors effectiveness in choppy water (waves) as well as the effect of surface motion of false alarms was determined by correlating the sensor response in each of the optical channels with variations wave height.

The test sensor was evaluated using a series of different petroleum products, under calm, flat surface conditions as well as under a simulated harbor chop with wave heights ranging from 0-18 inches (46 cm). The harbor chop conditions were created by mechanical generation of coherent waves emanating from the far end of the test tank combined with reflection from the far end to create surface motion through wave interference. The chaotic motion caused the sensor to pitch, heave and roll aperiodically on the water surface.

4.3.1.1 Gasoline Response

The first test was performed to evaluate the sensor response to gasoline. A sensor was placed into the test tank within a ring made by a 50-foot length of boom material as shown in Figure 4.1. The actual circumference of the ring was 45 feet after the ends of the boom were secured to each other. This corresponds to a total confined area of 160 square feet (ft) or 1.5×10^5 square centimeters (cm). Gasoline samples were dropped into the ring in two additions: a 200 ml

addition after 8 minutes in the water, then a 500 ml addition after 21 minutes. The sensor was programmed to record and transmit a measurement every 8 seconds. The resulting raw response and measured reference lamp energy is shown in Figure 4.2. An averaged version of the same data is shown in Figure 4.3 where the data was integrated using a six-point moving average.

It is clear from the charts that each of the three optical channels positively responded to the addition of gasoline. The initial 8 minutes has a flat response followed by an upward spike starting at the time of the first addition. This response tapered off over the next 10 minutes as the relatively high vapor pressure gasoline evaporated into the atmosphere. The second addition caused another somewhat higher spike that tapered off more slowly due to the higher volume added.

The lamp intensity, also plotted in Figures 4.2 and 4.3, is seen to be very stable over time with a pulse-to-pulse RMS deviation over the 70-minute duration of the test of less than 0.4%. Clearly the variations (noise) measured at each optical detection channel can be attributed to factors other than fluctuations in the output energy of excitation lamp.

The separate response of each optical channel is shown in Table 4.3.

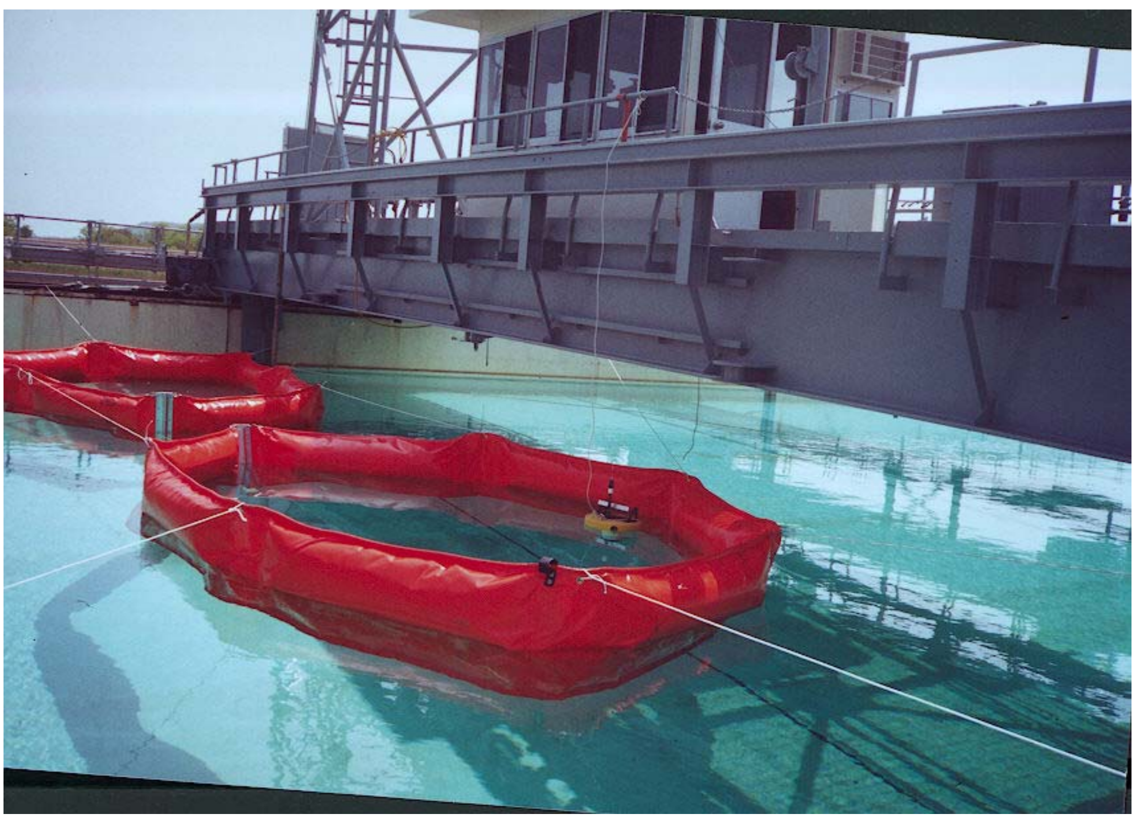


Figure 4.1 Spill Testing Within a 50-foot Boom.

It can be seen from Figures 4.2, 4.3 and Table 4.4 that Channel 3, the UV channel and also physically the first in the detection series, is the most sensitive to the presence of gasoline. Figure 4.4 shows the ratio of Channel 2 to Channel 3; dips correspond to increases in the overall signal level.

At the completion of measurements, the sensor was retrieved from the water and washed with a surfactant to remove any residual gasoline. The boom was lifted so that any remaining gasoline could be "pushed" away from the test ring using a fire hose. Once the test ring was relatively free of fuel, the boom was replaced, the sensor returned to the water, and preparations started for the next test. While the fire hose method was successful in removing nearly all of the remaining fuel, some small but detectable amount of petroleum remained within the ring generally causing an increase in the baseline and baseline variance or "noise" for each successive test.

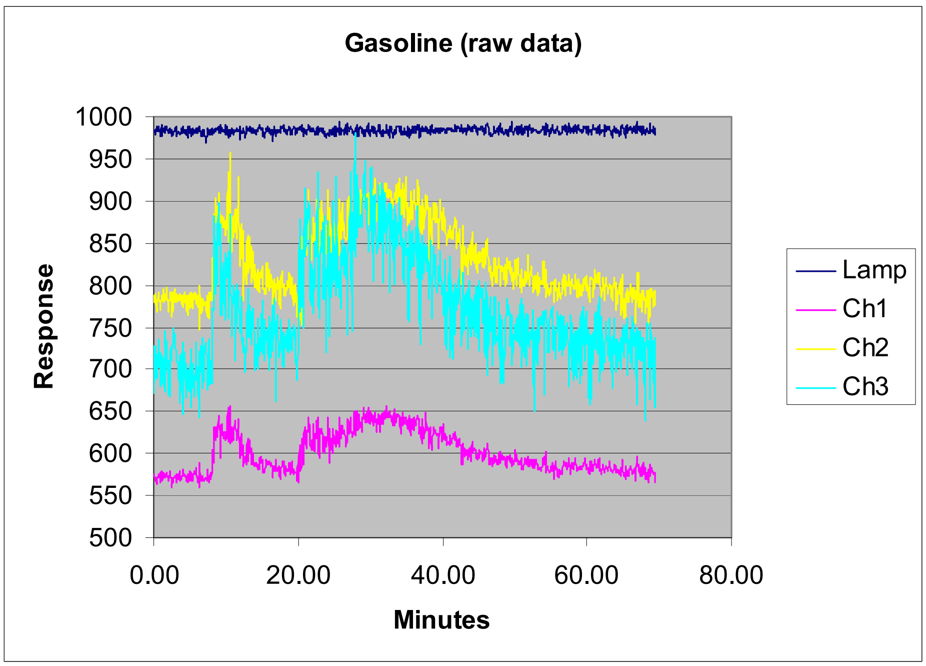


Figure 4.2 Gasoline Test Results Raw Data.

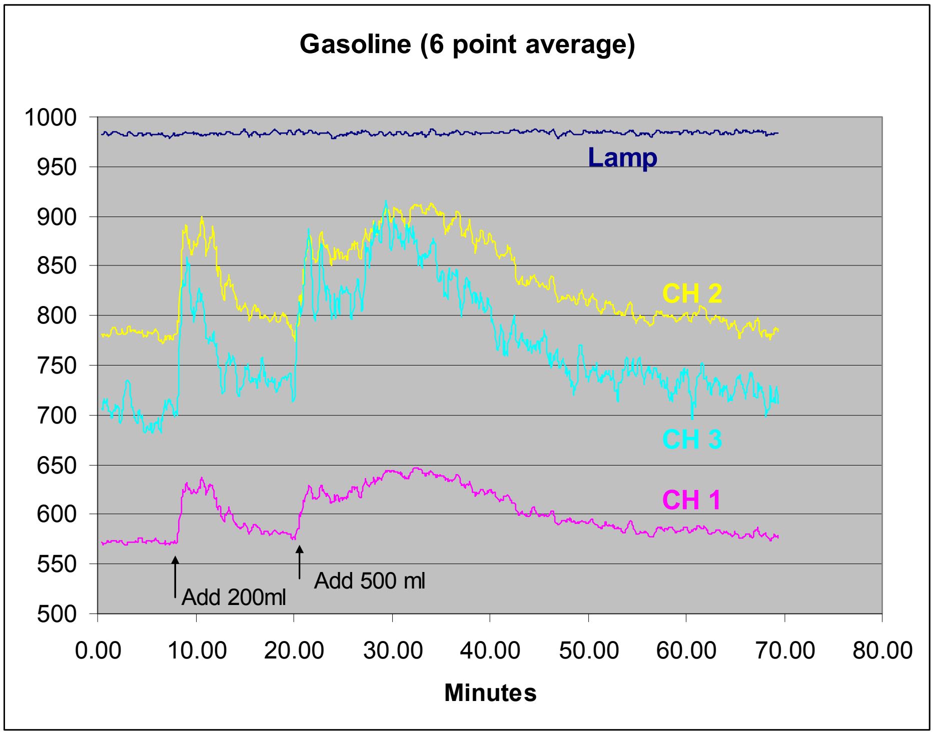


Figure 4.3 Integrated Sensor Response to Gasoline.

Table 4.4 Sensor Response to Gasoline

	Rms Baseline Noise	Signal Increase Due To 200ml Addition Of Gas	Signal-Noise (S/N) After 200ml Addition	Signal Increase Due To 500ml Addition Of Gas	Signal-Noise (S/N) After 500ml Addition
Channel 1 (>450nm)	4.83	55	11	70	15
Channel 2 (400-450nm)	8.88	99	11	121	14
Channel 3 (320-400nm)	23.7	120	5.1	178	7.5

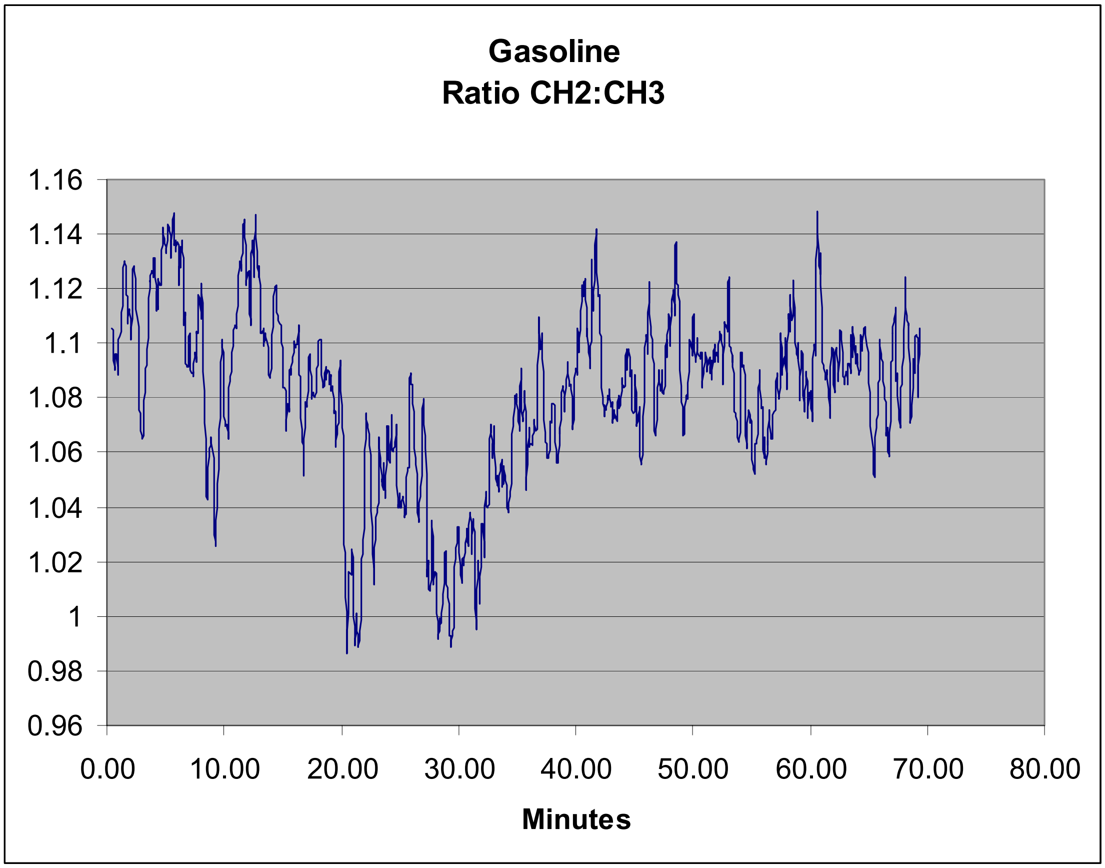


Figure 4.4 Sensor Response to Gasoline. Ratio of Optical Channel 2 to Channel 3.

4.3.1.2 Diesel Response

The sensor response to diesel fuel was determined next in the same way using the 50-foot boom to cordon off a portion of the tank, to which a sample of diesel was added. After establishing a baseline measurement, 200 ml of diesel no. 2 was added to the test ring. The sensor immediately responded on all channels as shown in Figure 4.6. Figure 4.7 shows the same data after 6-point moving average was calculated to smooth the results. After 20 minutes, wave action was introduced to evaluate the sensors ability to detect diesel in the presence of surface motion. The waves quickly built up to 10 inches in height. Figure 4.5 shows waves being generated in the test tank. The wave motion had the effect of causing the sensor to bob, causing portions of the fuel sample to spill over the boom, dispersing remaining sample throughout the test ring, and emulsifying a portion of the added fuel.

Figure 4.5   Wave Generation in the Ohmsett Test Tank.

The multichannel response is tabulated in Table 4.5. The data points used to determine background variation (standard deviation) are taken from the time interval prior to adding diesel. The "signal increase" values are taken after diesel was added but before wave generation started. The baseline variation was higher at the start of this the second test than for gasoline for reasons noted above, i.e. there was some residual petroleum from the earlier test remaining in the test ring. This essentially reduces the signal-to-noise ratio along with estimated detection limits. However the situation is very similar to what one would encounter at an actual waterfront facility where some detectable level of background petroleum is nearly always present.

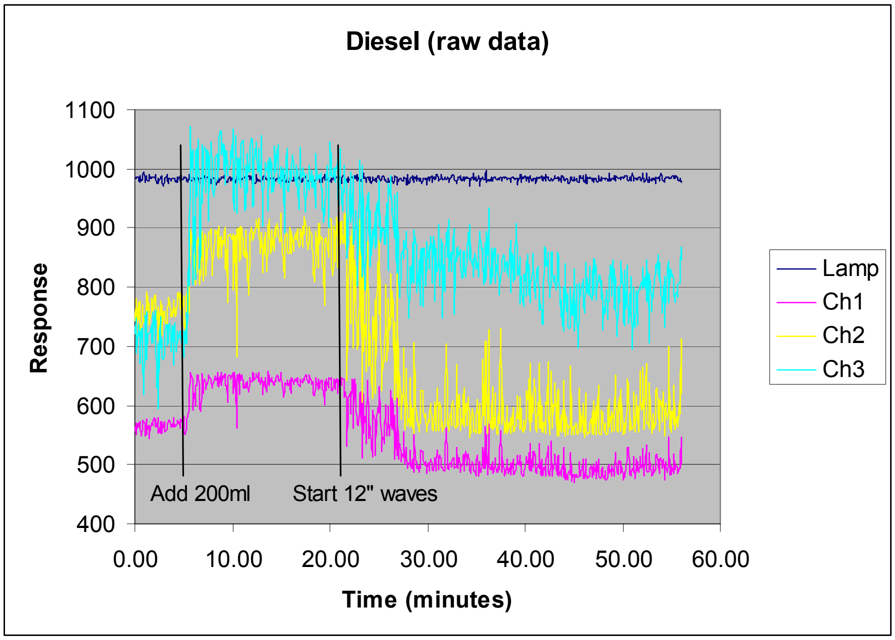


Figure 4.6 Sensor Response to Diesel, Raw Data.

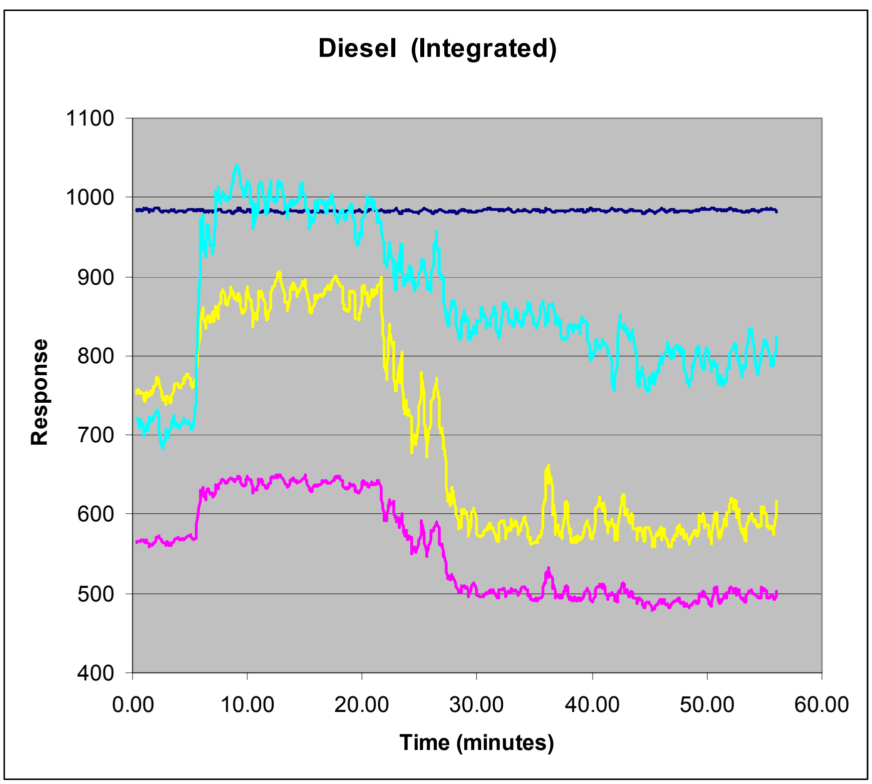


Figure 4.7 Sensor Response to Diesel, Six-point Moving Data Average.

The sensor response shown in Figures 4.6 and 4.7 is interesting in that Channels 1 and 2, after maintaining a relatively steady response to the added fuel, drop back to below base line within minutes after the waves begin. The Channel 3 response decreases as well but never drops to a level that's below four times background variance (S/N). The initial rise in all three channels can be attributed to the presence of the added petroleum on the water surface above the sensor. The signal decrease observed after wave action is initiated may be due to a combination of two factors. First, the mechanical motion of the waves causes the petroleum to disperse within the ring; it also causes some continual rate of petroleum loss due to splashing over the ring barrier, and it causes some of the petroleum to become emulsified and disperse beyond the test ring into rest of the tank. This would account for the steady signal decline throughout the first 10 minutes of wave action. The second factor influencing a baseline drop is likely a reduction in back-reflected excitation light.

In calm flat water, the excitation light can be partially reflected back through the optical detection system. A small portion of the excitation light may leak through the optical filter array causing a baseline offset. If the angle between the sensor and the surface water becomes greater than zero degrees, the less excitation light will be coupled back into the detection optics resulting in a reduced baseline. The effect is illustrated in Figure 4.8.

Channel 3 remained above baseline even in the presence of the waves because the fluorescence response to diesel at this wavelength was greater than the reduction due to a lowering of the baseline response. The sensor still detected the petroleum within the ring even during this wave-causing mechanical agitation.

Table 4.5 Sensor Response to Diesel

	rms baseline noise	**signal increase due to 200ml addition of diesel**	**signal-noise ratio (s/n) after 200ml addition**
Channel 1 (>450nm)	8.5	66.3	7.8
Channel 2 (400-450nm)	21.2	105.5	5.0
Channel 3 (320-400nm)	20.1	255.4	12.7

The ratio of optical Channel 2 to Channel 3 for diesel is shown in Figure 4.9. The relative intensity of Channel three increases from .95 to 1.1 as diesel was added, then increased again to 1.4 as waves were introduced. The change in the Channel 2 to channel 3 ratio can be used to confirm the presence of oil and may potentially be used to distinguish between petroleum types.

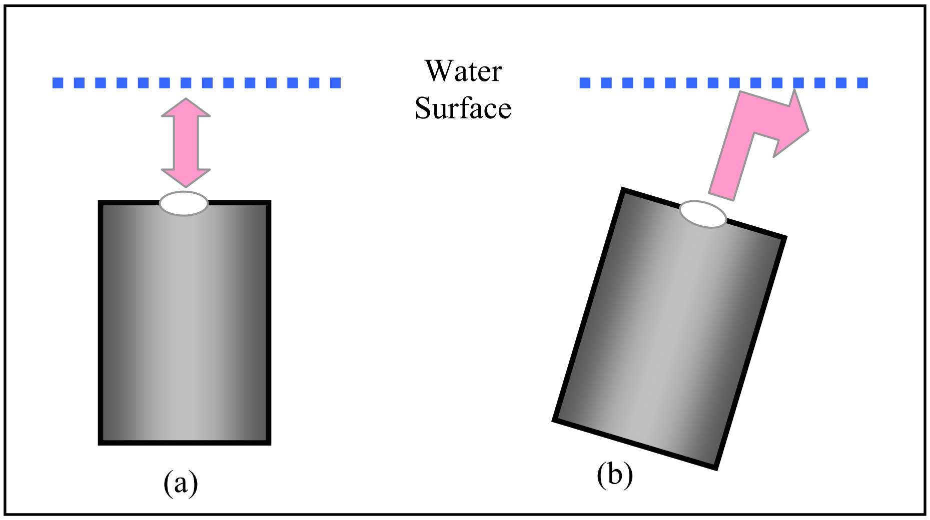


Figure 4.8 Effect of Surface-sensor Angle on back-reflected Excitation Light. (a) Zero degrees in calm water, some light reflected back into optical detector. (b) The angle between the sensor and the surface reduces amount of excitation light returned by reflection into the detection optics.

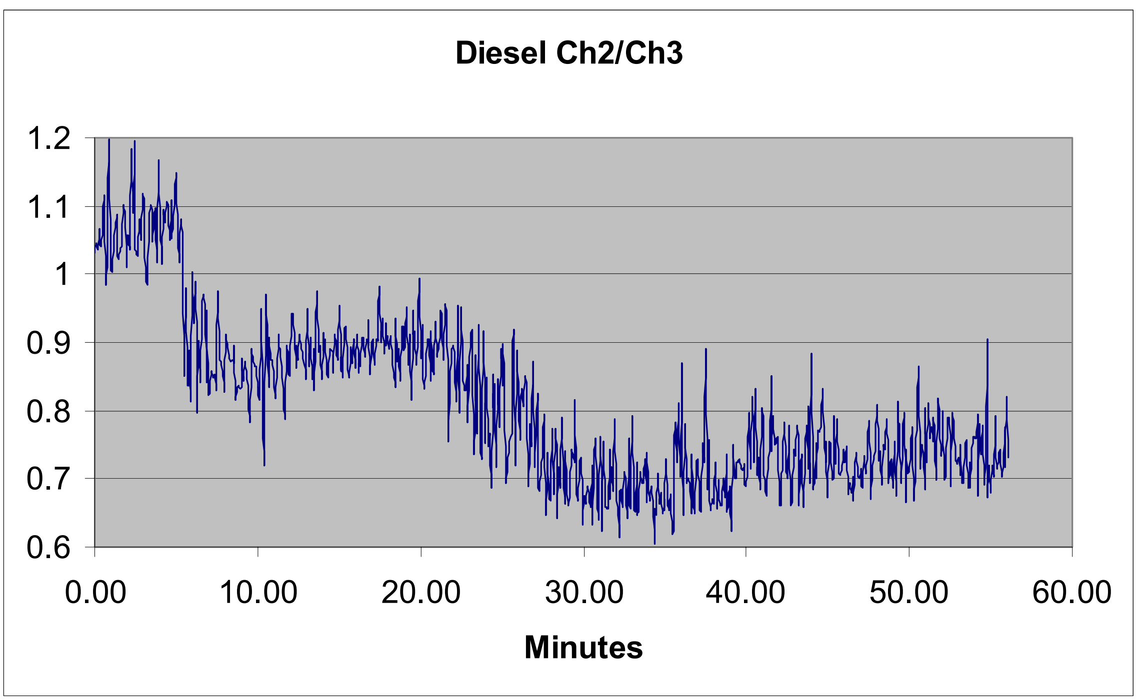


Figure 4.9 Ratio of Optical Channels 2 to 3 for Diesel Fuel.

4.3.1.3 Lube oil response

The sensor response to lube oil was tested with and without waves using a petroleum product provided by Ohmsett, a light oil referred to as Hydrocal. Two 100 ml additions of Hydrocal were added to the test ring, the first 100 mls after seven minutes of baseline recording, and the second 100 mls after 13 minutes. At the 24-minute mark, waves were initiated and ramped up to a maximum height of 33 cm over 26 minutes and a series of four successive step increases. The wave generator was then shut down allowing surface motion to return to a quiescent state. The raw data results are shown in Figure 4.10 with the integrated data charted in Figure 4.11.

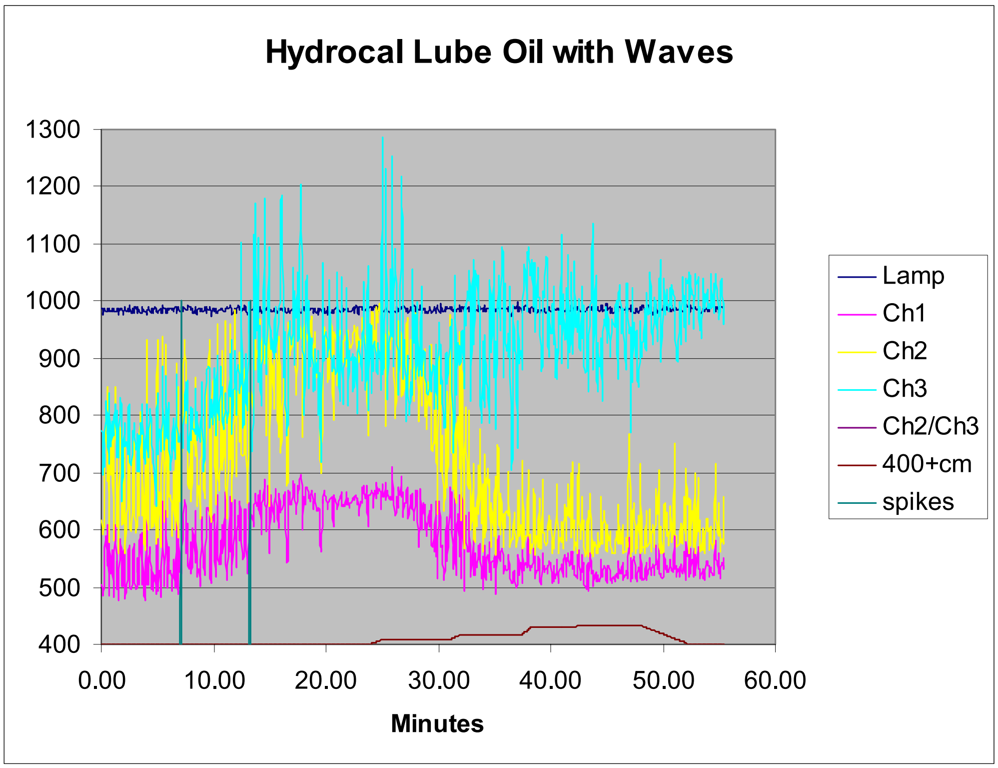


Figure 4.10 Sensor Response to Hydrocal Lube Oil, Raw Data.

The average response of each optical channel to Hydrocal is tabulated in Table 4.6 along with signal-to-noise measurements.

Each of the three optical channels reaches peak response within eight minutes of the first addition. As with diesel, the response of Channels 1 and 2 decreased as waves were introduced into the test system. The response of Channel 3 maintained its mean peak response during wave ramp-up and ramp-down.

The Hydrocal test demonstrated two performance criteria. First, that the *Spill Sentry* sensor has a positive response to lube oil. Second, using Optical Channel 3, the response was independent of the wave action. As with the other tested petroleum products, Channel 3 exhibited the strongest response to the added oil. Channel 3 also appears to be the least affected by surface motion. An

additional factor that may influence the optical response to waves may be a partitioning of the oil sample between emulsified and dissolved phases in the water column and continuous phase floating in the surface. Agitation from waves can be expected to increase mechanical mixing leading to emulsification and dissolution of the sample, particularly the lighter aromatic components. The more soluble aromatics such as naphthalene and benzene would have a stronger response in the UV region detected by Channel 3. This effect would coincide with a decoupling of the sensor from the surface and hence reducing the Channel 2 and Channel 3 signals due to heavier hydrocarbon components.

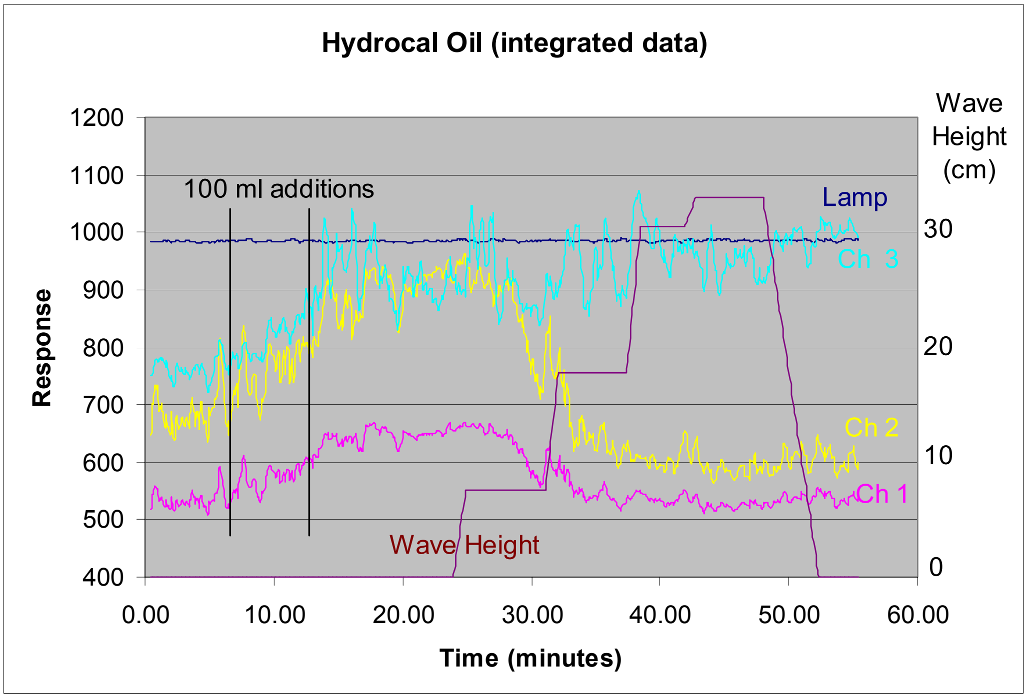


Figure 4.11 Sensor Response to Hydrocal, Six-point Moving Average.

Table 4.6 Averaged Sensor Response to Hydrocal Lube Oil.

	rms baseline noise	signal increase due to 200ml addition of oil	signal-noise ratio (s/n) after 200ml addition
Channel 1 (>450nm)	42.8	123.7	2.9
Channel 2 (400-450nm)	87.8	252.5	2.9
Channel 3 (320-400nm)	34.3	169.0	4.9

The ratio of signal produced in Optical Channel 2 to Optical Channel 3 during the Hydrocal test is represented in Figure 4.12. The key feature is a significant decrease in the ratio that corresponds with the initiation of waves and continues even after the mechanical agitation has ended and the surface has returned to a quiescent state.

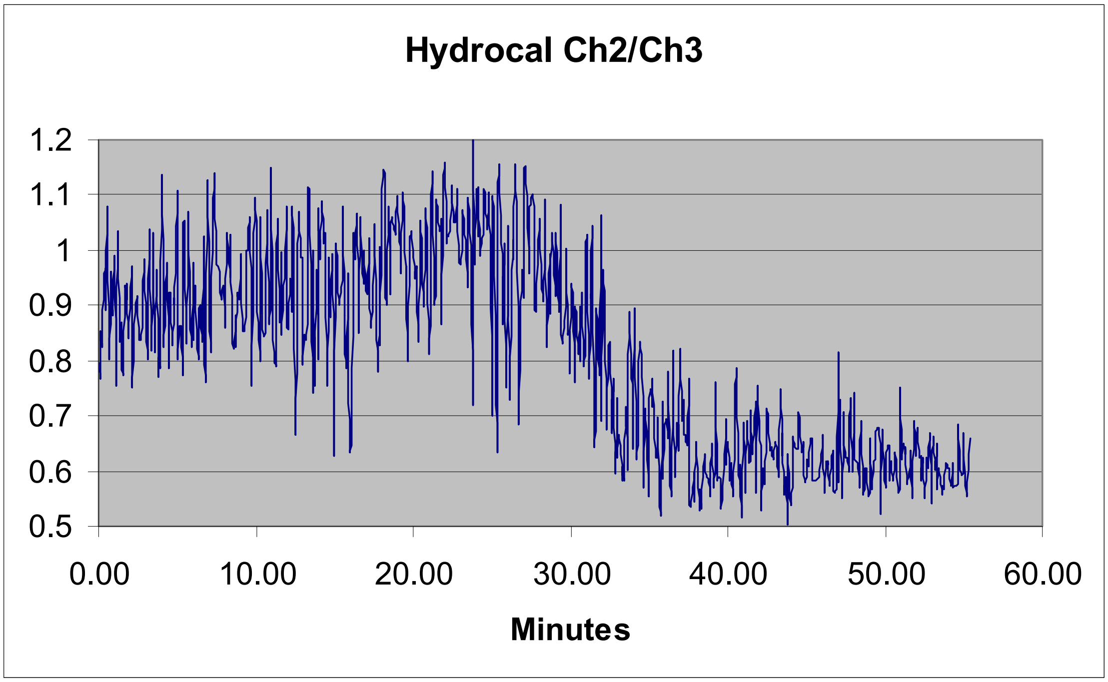


Figure 4.12 Ratio of Optical Channel 2 to 3 During Hydrocal Ring Test.

4.3.1.4 <u>Effect of surface motion (waves and chop)</u>

The Spill Sentry sensor's ability to positively detect petroleum in the presence of significant wave action (simulated harbor chop) was observed in the diesel and Hydrocal tests. The objective of the next test was to evaluate whether wave action alone, without the presence of petroleum on the water surface, might create a sensor response leading to false alarms. The sensor was once again placed within the test ring. No additional petroleum was added to the ring until 60 minutes after data collection began. The addition was used to verify that the sensor was in fact still responding to oil. The data for each channel along with the wave height information is plotted below in Figure 4.13.

The initial signal at each channel was somewhat elevated at the start of the test due to a small amount of petroleum remaining within the ring after the previous tests. The signal levels quickly subside after waves are started due to dissipation of the remaining petroleum and also due, at least in part, to the reduced back-reflection effect.

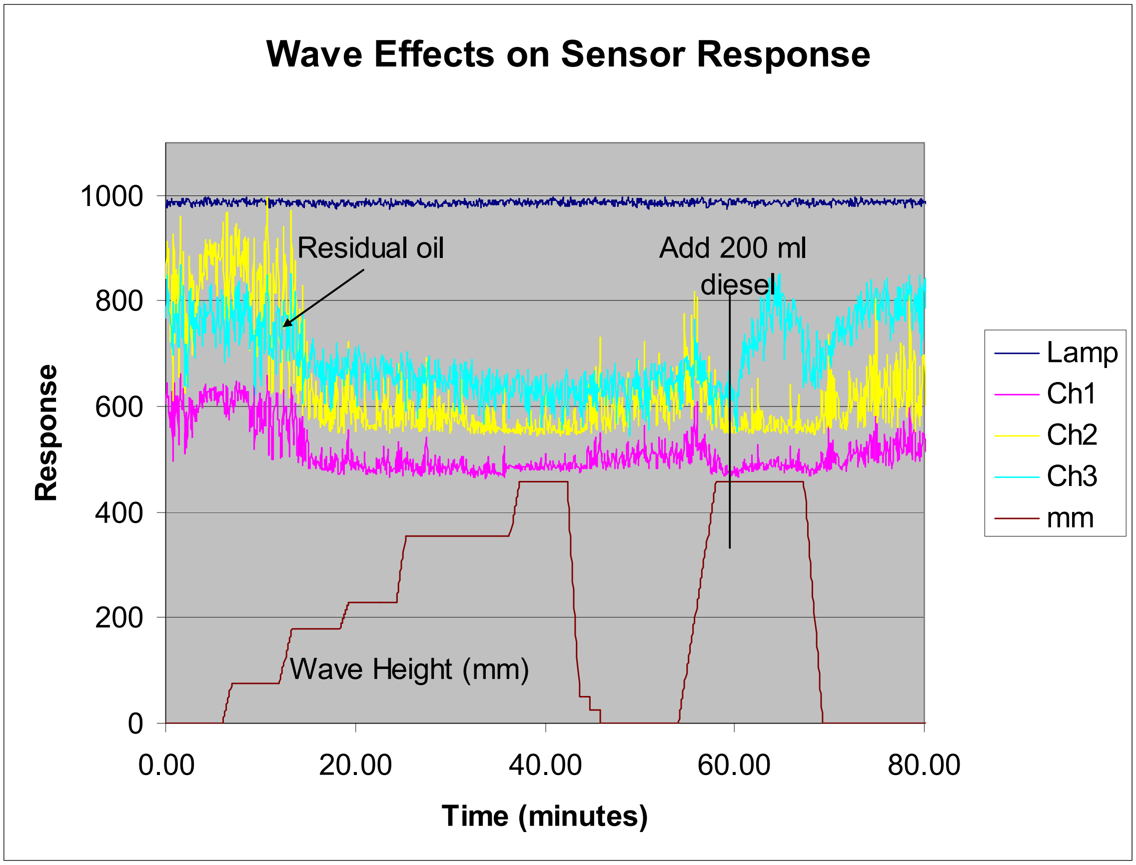


Figure 4.13 Background Sensor Response as Wave Height is Altered.

Table 4.7 Correlation Between Optical Signal and Wave Height

	CH 1	CH 2	CH 3
Correlation ®			
All data up to fuel addition (60 minutes total, 0-18" waves)	**-.57**	**-.54**	**-.46**
Excluding first 20 minutes (40 minutes total, 0-18"waves)	**-.43**	**-.35**	**-.09**
Shared variance (r^2)			
All data up to fuel addition (60 minutes total, 0-18" waves)	**.32**	**.29**	**.21**
Excluding first 20 minutes (40 minutes total, 0-18"waves)	**.19**	**.13**	**.01**

Once the initial background signal subsided, the response of each of the optical channels stayed relatively constant throughout the first wave ramp-up, in which the wave height was raised up to 18 inches over five step increases. The optical response continued to remain relatively steady as the wave generator was stopped and the surface waves returned back to a calm state. Wave height was then ramped up quickly again back to an average wave height of 18 inches. The optical response showed a small but measurable increase during the intermediate quiescent period then rapidly dropped again as the second wave ramp-up was initiated. It is possible that this may have again been due to the back-reflection effect. At the 60 minute mark, at peak wave generation, 200ml of diesel was added to the test ring. Optical Channel 3 responded strongly to the diesel whereas the other two channels remained unresponsive. The response of Channel 3 demonstrated that the sensor was responding normally, and that it could detect a diesel spill even in the presence of an 18-inch surface chop. The response of Channel 3 decreased the increases again as the test was continued. This effect was caused by the sensor moving away from, then back into, the diesel plume. The response of all three channels increased again as wave generation was halted and the water surface once again returned to a calm state.

The correlation between the signal at each optical channel and wave height is shown in Table 4.7. The correlation was calculated using two sets of data. The first covers the entire 60 minutes of the wave test. The second data series uses a subset of the first by ignoring the first 20 minutes. The initial 20 minutes corresponds to the time interval in which residual petroleum significantly affected the sensor response. The results indicate a very weak negative correlation between the sensor response and wave height. The negative sign of the correlation is attributable to the back-reflection effect. The small magnitude of the correlation, particularly for Channel 3, is evidence that the sensor response is significantly independent of surface motion and that surface waves will not generally produce a false response or alarm.

Sensor response versus wave height is plotted in Figure 4.14. From the figure it can be seen that there is very little correlation between wave height and sensor response. The range of response values is larger at smaller wave heights. This may indicate an effect on response up to a threshold wave height after which the response is essentially decoupled from surface interactions.

Figure 4.15 charts the optical response ratios during the wave test. The Channel-3-to-Channel-2 ratio increased initially due to the combined impact of petroleum dissipation and the back-reflection effect. The ratio increased sharply once again as diesel was added to the test ring. The Channel-2-to-Channel-1 ratio increased slightly during quiescent periods then decreased as wave height increased. The inverse relationship is expected from the back-reflection effect.

4.3.1.5 <u>Ability to discriminate between petroleum products</u>

The *Spill Sentry* system has the potential to distinguish between different petroleum products by utilizing the information contained in all three optical channels.

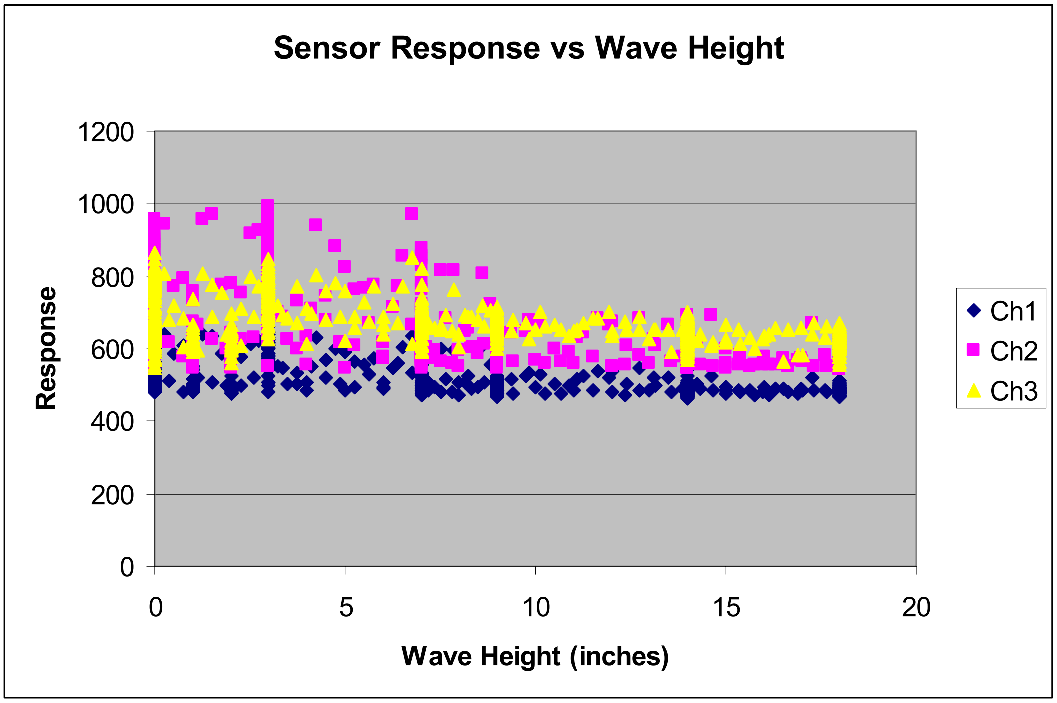


Figure 4.14 Sensor Response vs. Wave Height.

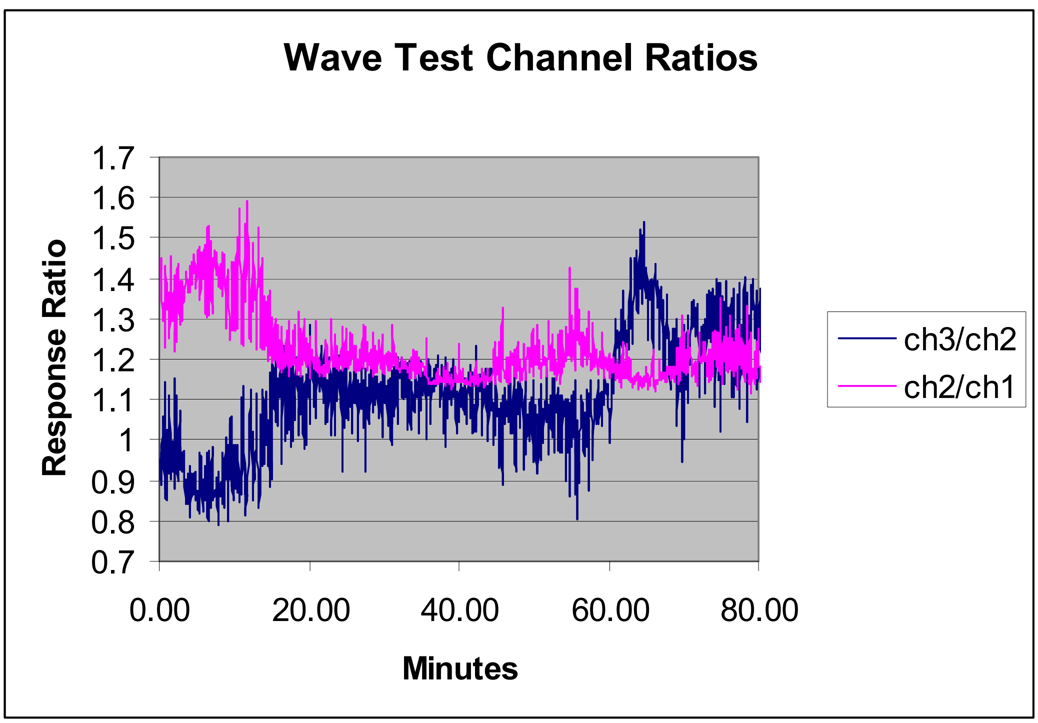


Figure 4.15 Channel Ratios During Wave Test.

Typically, this is done by comparing the response ratios of the channels. Lighter products and dissolved phase constituents will have a stronger response in the UV corresponding to Channel 2. Heavier products will cause a response in Channel 3 while also causing an increased response in the blue spectral region measured by Channel 2. Channel 1 is expected to show and increase in response to non-petroleum fluorophores such as chlorophyll or for solid material or debris that reflects light directly back into the sensor. The Channel 1 response can be used to distinguish false positives from actual spills.

During the Ohmsett study, the sensor response ratios to four different petroleum products, along with a non-petroleum fluorophore and blank background, were compared to determine the effectiveness of using the ratio method to distinguish between petroleum types. The products tested were: gasoline, diesel fuel, Hydrocal lube oil, crude oil and fluorescene as the non-petroleum fluorescer. The results are shown below in Figure 4.16.

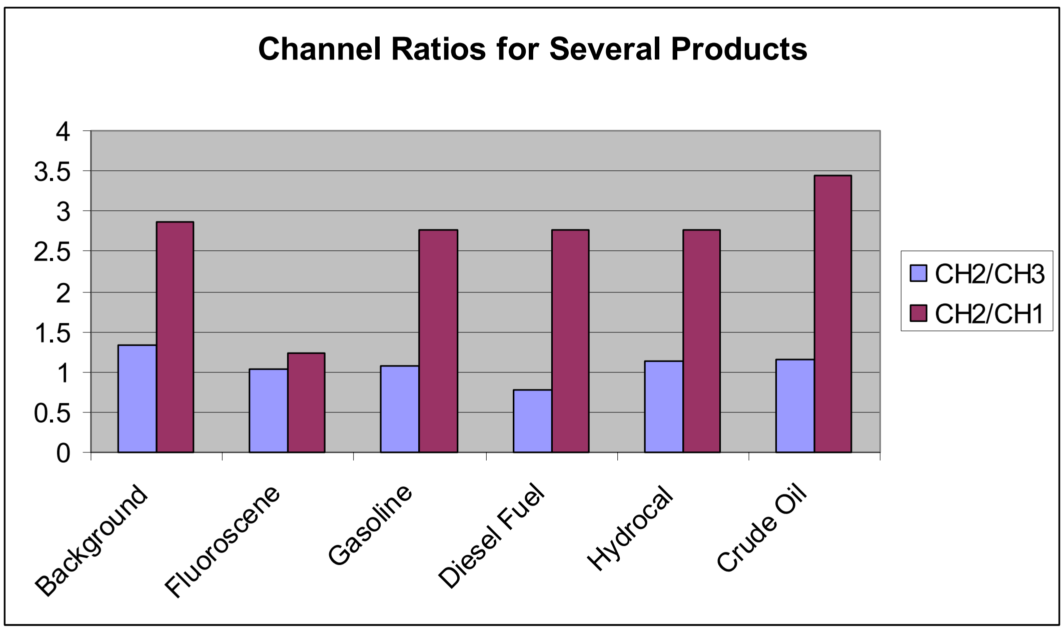


Figure 4.16 Channel Ratios for Several Products.

From Figure 4.16 it can be seen that crude oil, the heaviest of the products tested, is the only material causing a significant increase in the Channel 2 to Channel 1 response ratio. Fluoroscene, the non-oil, is the only product yielding a significantly reduced Channel 2 to Channel 1 ratio. The variation among the other petroleum products is mostly contained within the channel 2-3 ratio. A better view of the channel 2-3 ratio for each of the tested products is shown in Figure 4.17. From the Channel 2-3 ratio, diesel fuel and background stand out as clearly distinct from the other products.

The spectral separation of each of the products is more clearly seen in Figure 4.18 where the Channel 2-1 ratio is plotted against the Channel 2-3 ratio. One could distinguish

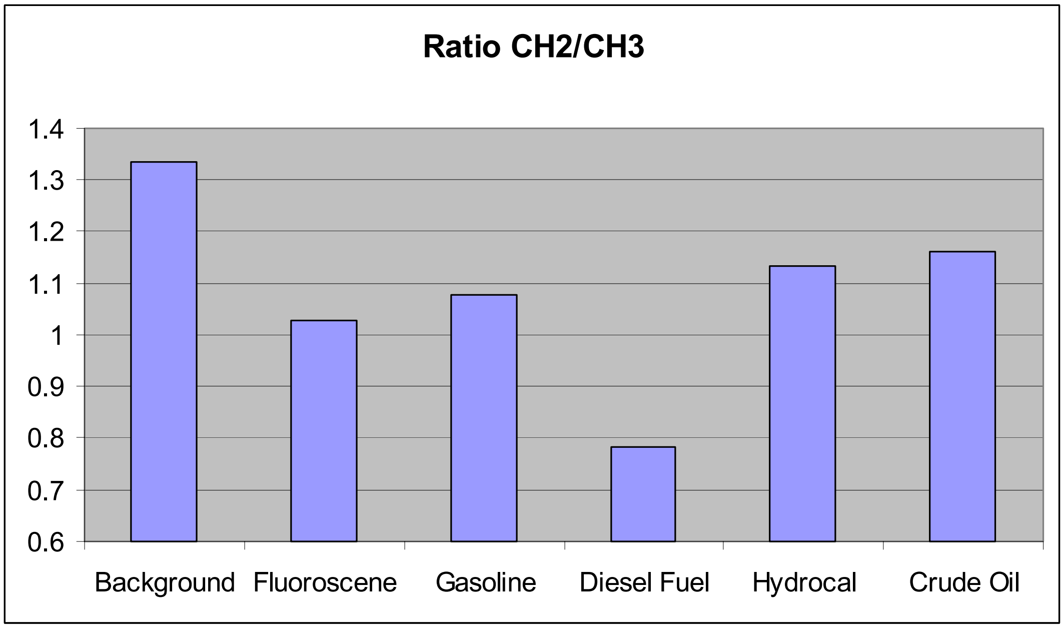


Figure 4.17 Ratio of Channel 2 to Channel 3.

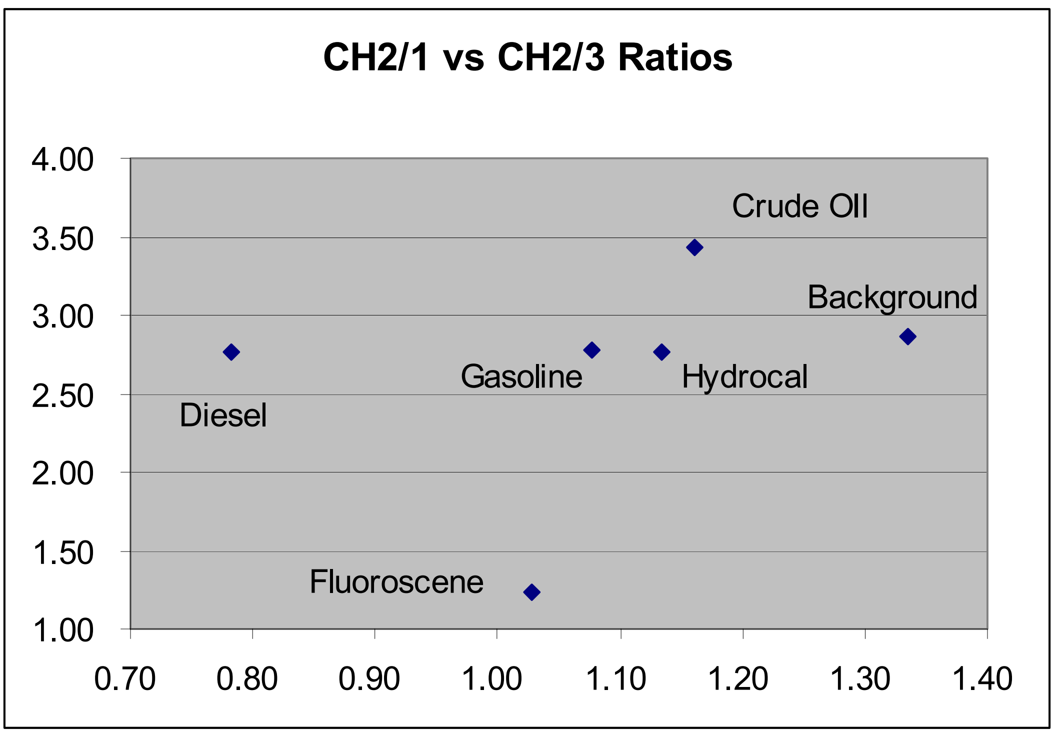


Figure 4.18 Channel 2/1 Ratio Plotted Against the Channel 2/3 Ratio.

petroleum from non-oils by using a classification boundary corresponding approximately to the y= 2.0 or y= 2.5 line of Figure 4.17. The separation in Figure 4.17 would indicate that the separate products could be distinguished under ideal circumstances. However, as seen in the previous tests, the channel response ratios can change depending upon surface activity (back-reflection effect). This was an unexpected finding and the channel ratios were not originally tested under wave conditions for each of the products. As a result, while it appears that the *Spill Sentry* system can distinguish between different fuel products, it is still unknown whether the variance in channel ratios due to wave action would impact these results.

4.3.1.6 Ohmsett Test Issues

During the Ohmsett testing the baseline or background sensor response generally tended to show an increase as the study progressed. The background measurements are plotted in Figure 4.19. Because it was virtually impossible to completely clean the surface within the ring after each test, successive tests experienced a rising background. In addition, emulsified and dissolved petroleum within the tank also increased throughout the study. The rising background, though clearly visible in the data, ultimately had little impact on meeting the test objectives.

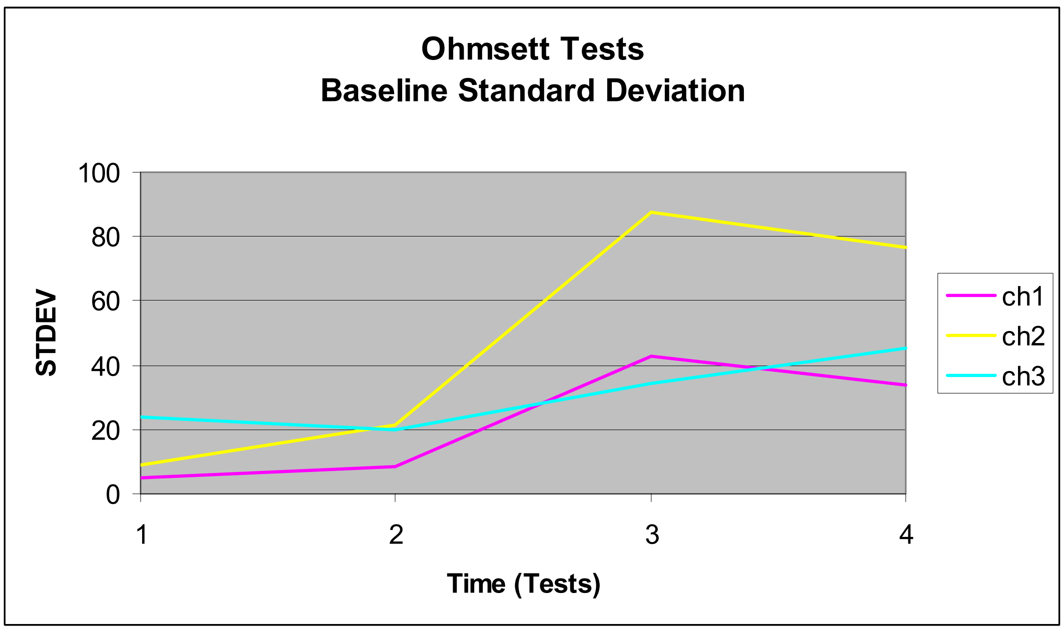


Figure 4.19 Change in Sensor Background Response.

Another issue is the level of signal variance or "noise"due to inhomogeneous oil distributions. If the petroleum additions were uniformly distributed throughout the test ring, a 200 ml aliquot would correspond to a film thickness of approximately 13 micrometers. However, it was observed during the tests that the added fuel was not uniformly distributed but tended to pool and cluster. This was especially the case for heavier fuels. An example of a 200ml addition of crude oil to the test ring is shown in Figure 4.20. Crude oil is especially easy to photograph because of its very dark coloration; but similar results were observed for all petroleum products.

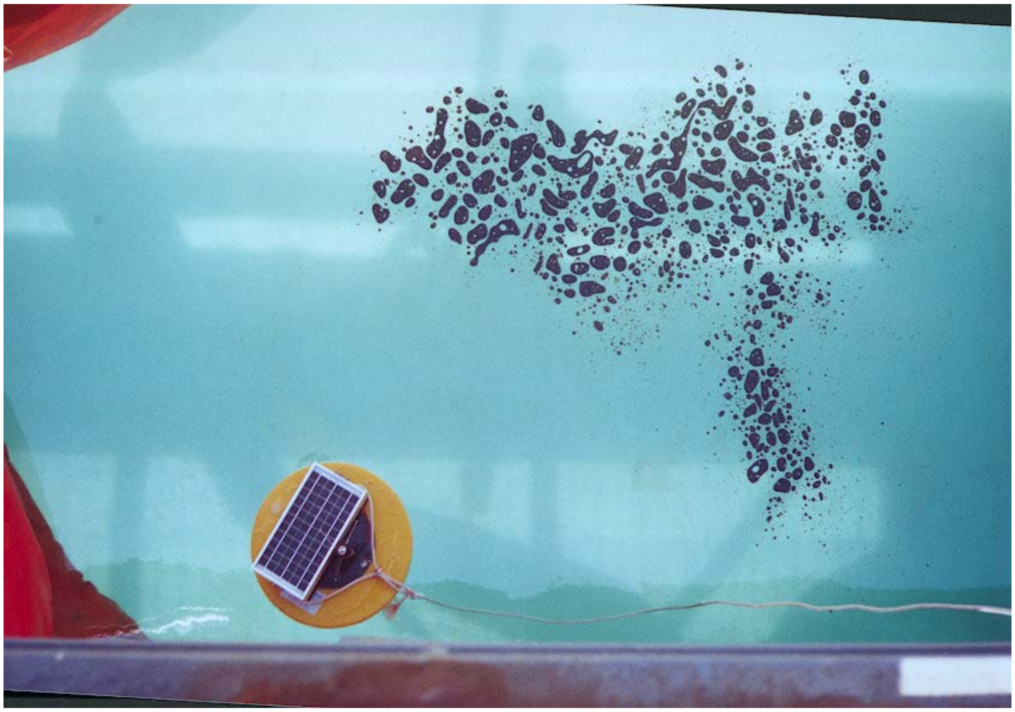


Figure 4.20   Crude Oil in the Test Ring.

What cannot be seen in the picture is a very thin film of oil spread over a broad area of the ring. It is this thin film that the sensor detects while the bulk of the material is still floating at some distance from the sensor. Mechanical agitation from wave action serves to spread the petroleum more evenly throughout the ring during wave tests but the distribution is far from homogeneous. Signal noise appears to increase as the relative motion of the sensor moves it across the inhomogeneous pockets of oil. It is important to recognize that this type of variance is distinct from possible electronic noise or ambient light noise that has nothing to do with the oil content of the water. The signal-to-noise ratios during this test are more a function of actual petroleum distribution than other noise factors.

Signal variation can be significantly reduced by averaging. An example is shown in Figure 4.21, a plot of the Channel 3 (oil) and Channel 1 (non oil) responses to diesel fuel obtained during the first Ohmsett test in September. The signal, corresponding to a series of measurements collected every 20 seconds, was processed as a three-minute moving average. Many of the high frequency variations are eliminated and the overall apparent signal to noise ratio is improved. This same methodology could be employed with sensors in the field to smooth out short-term signal variance. The trade-off is a slower response time, in this case a three-minute versus 20-second response.

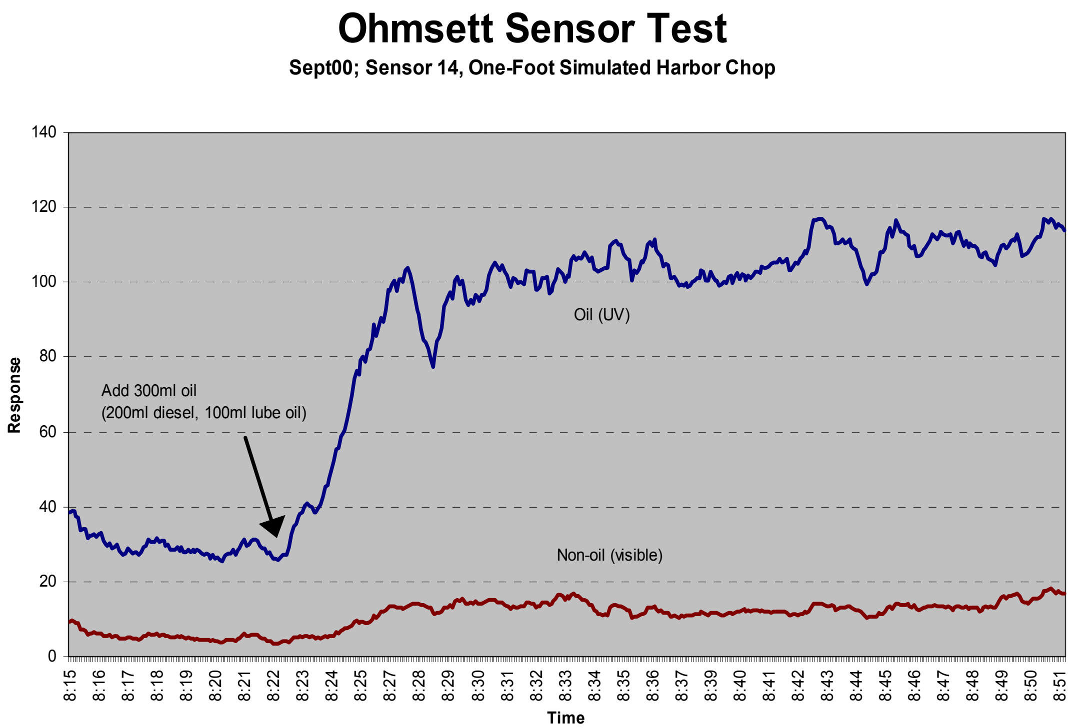


Figure 4.21 Channel 3 Response to Diesel in One-foot Waves.

4.3.2 Field Testing

4.3.2.1 <u>Oil Detection</u>

No significant spill events occurred during the demonstrations at Pearl Harbor, Langley, or Puget Sound. One spill occurred very near one of the waterfront sensors at Norfolk within the first month after the sensor system was installed. This was the only significant spill event at Norfolk during the demonstration. The *Spill Sentry* system did not alarm on this spill because of concurrent radio interference that prevented the sensor data from reaching the base station computer. The radio interference problem was subsequently solved. However, the one opportunity to detect a spill during the evaluation was missed. A follow-on, post ESTCP demonstration of the *Spill Sentry* system at San Diego Harbor has been successful in providing early detection of one actual spill (out of one opportunity). Data and circumstances describing this event are to be published elsewhere (Publication TBA. This data, obtained post ESTCP demonstration, can be included if appropriate).

4.3.2.2 <u>Window Fouling</u>.

The use of ultra violet light as a germicidal measure to prevent window fouling was highly effective at each of the demonstration sites. This unique application of an optical method for the prevention of underwater biofouling has potential application in many other underwater technologies. An example of fouling prevention is presented in Figures 4.22, 4.23 and 4.24.

Figure 4.22 Sensor Fouling at Pearl Harbor, HI.

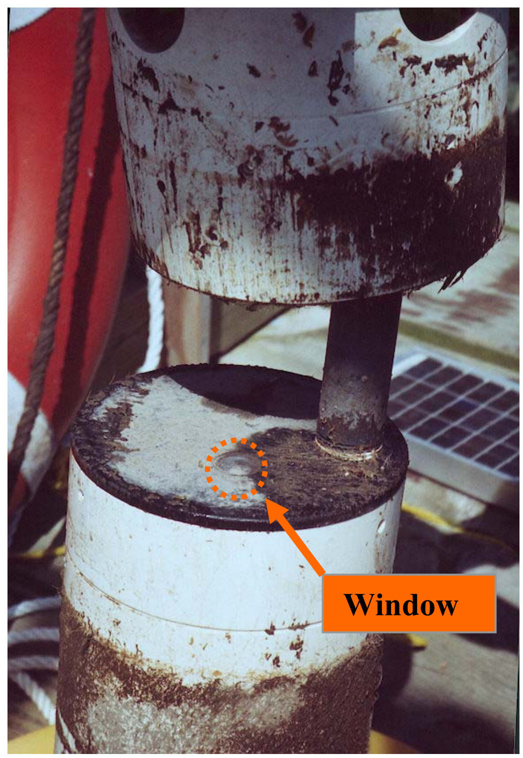
Pearl Harbor exhibited the worst fouling conditions of any of the demonstration sites. Biota accumulated on the in-water sensors at a much faster rate than the other cold water locations. Figure 4.22 shows two sensors pulled out of the water at Pearl Harbor after just 30 days exposure. Neither sensor was treated with an antifouling coating prior to deployment. There is significant biofouling up to and just beyond the water line. A close up of one of these sensor housings, shown in Figure 4.23, shows two of the crabs found living on the sensor. Other animals found on the sensor included numerous shrimp, mollusks and tube-worms. Figure 4.24 depicts the optical window on top of the fouled sensor canister. It remained free of biofouling while the surrounding surface was heavily fouled. Some encroachment at the window periphery is evident; the fouling never extended beyond the levels shown in the photo. For the remainder of the deployed time at Pearl Harbor, the sensor housings and floats were treated with cuprous oxide based antifouling paint to minimize periodic cleaning efforts. Sensor housings at the other demonstration sites were also painted with a copper based antifouling coating to minimize cleaning maintenance.

Figure 4.23 Close-up of Fouled *Spill Sentry* Buoy.

Figure 4.24 Fouling around Optical Window.

The only demonstration site to have any issue at all with window fouling was Langley AFB. The sensor at Langley was deployed in a river with high sedimentation. A very fine layer of silt deposited on the sensor, including the optical window, within the first 90 days of deployment. Further study showed that the silt layer did not increase beyond the original detected amount. The silt deposition rate appears to have been in equilibrium with the rate at which it was washed away by river currents and disturbances. The small amount of light scattering due to the silt layer did not impact sensor operation while underwater. A photograph of the sensor fouling at Langley AFB is shown in Figure 4.25. The total amount or rate of silt deposition was too small to be accurately measured. Though sediment deposition was not a significant issue, AML has reported difficulties in deploying *Spill Sentry* systems in highly turbid inland waterways of northwestern Canada. Since the sensor relies upon optical transmission through the window and water column above the window, turbidity and sedimentation may limit deployment in some locations.

(a)



(b)

Figure 4.25 Sensor Fouling at Langley AFB. (a) Sensor Exterior. (b) Sensor Window.

4.3.2.3 <u>False Alarms</u>

For the purposes of this report, a false alarm is any event that triggers a *Spill Sentry* alarm when a petroleum spill has not actually occurred. During the demonstrations, false alarms did occur; however, the false alarm rate due to a non-petroleum substance or signal error was zero. All false alarms were caused by setting the sensor alarm threshold too low, thereby allowing high background levels to trigger an alarm.

The *Spill Sentry* system alarms when detected oil reaches a user-selectable threshold above background oil levels. If it is assumed that the variation in background oil levels is normally distributed, which experience has shown it is, a two-standards deviation threshold should result in an average of 2.28% of all background data points triggering an alarm. A three-standard-deviation threshold should result in 0.14% of background data points causing a false alarm. Setting an even higher threshold makes sense if the user only wishes to respond to large spills. For example, a one-gallon spill will trigger an alarm in most locations, i.e. it represents a significantly higher amount of surface oil than normal background levels. However, a spill response team may not need to mobilize for such a small spill.

Throughout the demonstrations, the alarm threshold was set to either two or three standard deviations above background. The threshold setting for a deployed sensor may be set much higher, i.e. 4 standard deviations or more to avoid false positives. A lower threshold was chosen for the demonstration tests to improve the likelihood of detecting an actual spill. For threshold setting, there is an always present compromise between minimizing the probability of a false alarm and maximizing the probability of detecting an actual petroleum spill.

Sensor measurements were obtained and transmitted every three minutes. This corresponds to 480 measurements per day. The expected false alarm rate is therefore:

Two standard deviation threshold : 0.0014 * 480 = 0.65 / day
Three standard deviation threshold: 0.0228 * 480 = 10.9 / day

The actual average false alarm rate is shown in Table 4.8. The false alarm rate during the demonstration tests significantly exceeded the target objective of less than one false alarm per month. The alarm rate would be dramatically reduced by simply raising the alarm threshold to four standard deviations or higher.

Table 4.8 Average False Alarm Rate at Each Demonstration Site

	PSNS	Norfolk	Langley	Pearl
Two std dev threshold	16	9	11	7
Three std dev threshold	1.1	0.8	N/A	1.2

4.3.2.4 Reliability

Spill Sentry system reliability was evaluated separately for: the sensor itself, the network and computer system, and the communication system. Overall, the system fell short of meeting the 99% up-time reliability objective. A substantial of down-time can be attributed to: network reliability, radio frequency interference, and physical storm damage to the in-water sensors. Much of these effects were a result of inexperience from having never before deployed the system in a extended field environment. Lessons learned from the demonstrations will directly lead to significantly improved system reliability in future deployments.

Table 4.9 Percentage of System Down-time

	PSNS	Norfolk	Langley	Pearl
Network down (does not affect alarming)	21%	8%	0%	0%
Telephone line problem (affects alarming)	0%	12%	52%	37%
Radio transmission problem (interference)	3%	37%	0%	0%
Sensor damaged	23%	25%	4%	8%
Other	6%	11%	10%	7%
Total down-time (some problems concurrent)	35%	50%	56%	46%

4.3.2.5 Maintenance

As with reliability, the *Spill Sentry* maintenance was evaluated in terms of: sensor maintenance, network and computer system maintenance, and communication system maintenance. Routine maintenance of the in-water sensors involved semiannual cleaning and painting. It also included sensor retrieval and replacement for repair or assessment. Computer system and network maintenance involved making occasional enquiries to local IT staff regarding unexpected changes to IP addresses, network down-time, security issues, etc. It also included computer storage disk (data) management. Communication system maintenance involves troubleshooting radio interference problems. This is limited to the first few weeks or months of an installation. Once a robust radio communication link is established, very little additional maintenance is needed. Routine user maintenance at each of the demonstration sites averaged less than the two hours per sensor per month target.

4.3.2.6 Ease of Use

Ease of use was evaluated through informal interviews conducted with local users. A key focus was the effectiveness and usability of the user software interface. Overall users were very satisfied with the convenience of using the Web based interface. Throughout the demonstrations, user suggestions for improvements to the software were incorporated into the design. Example screen shots of the *Spill Sentry* software used during the demonstrations are shown in Figures 4.26 and 4.27.

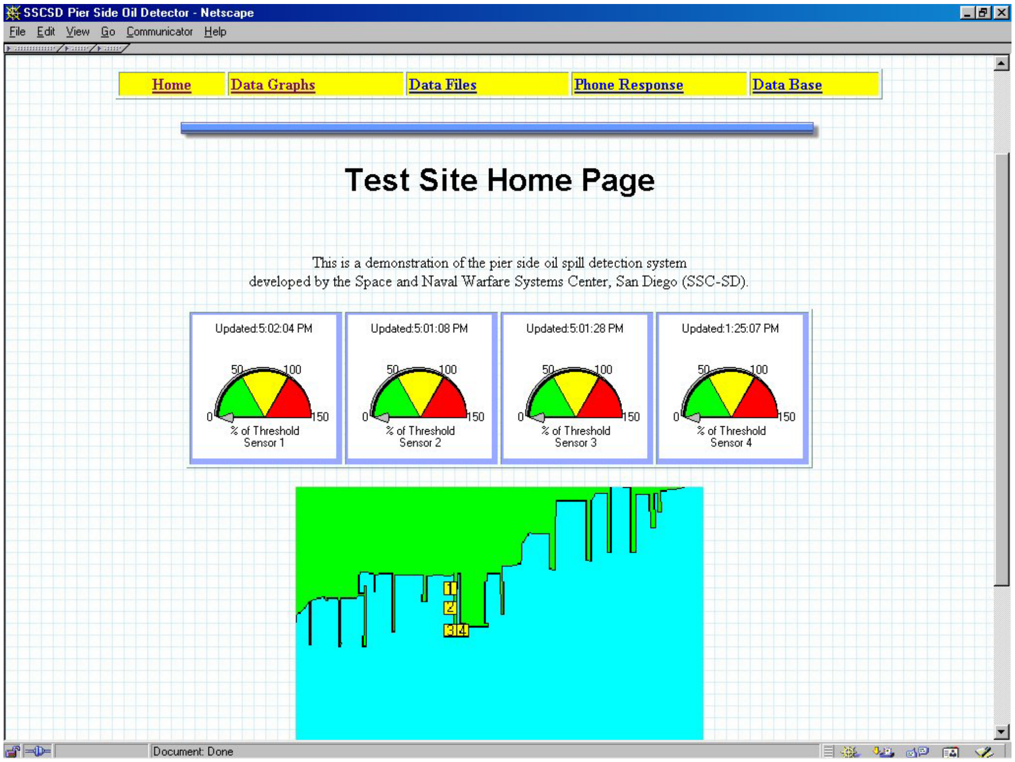


Figure 4.26 User Web Interface.

Time series charts were modified to make them simpler and easier to interpret. Detection levels were displayed as virtual gauges to facilitate rapid assessment without having to examine and interpret the streaming data.

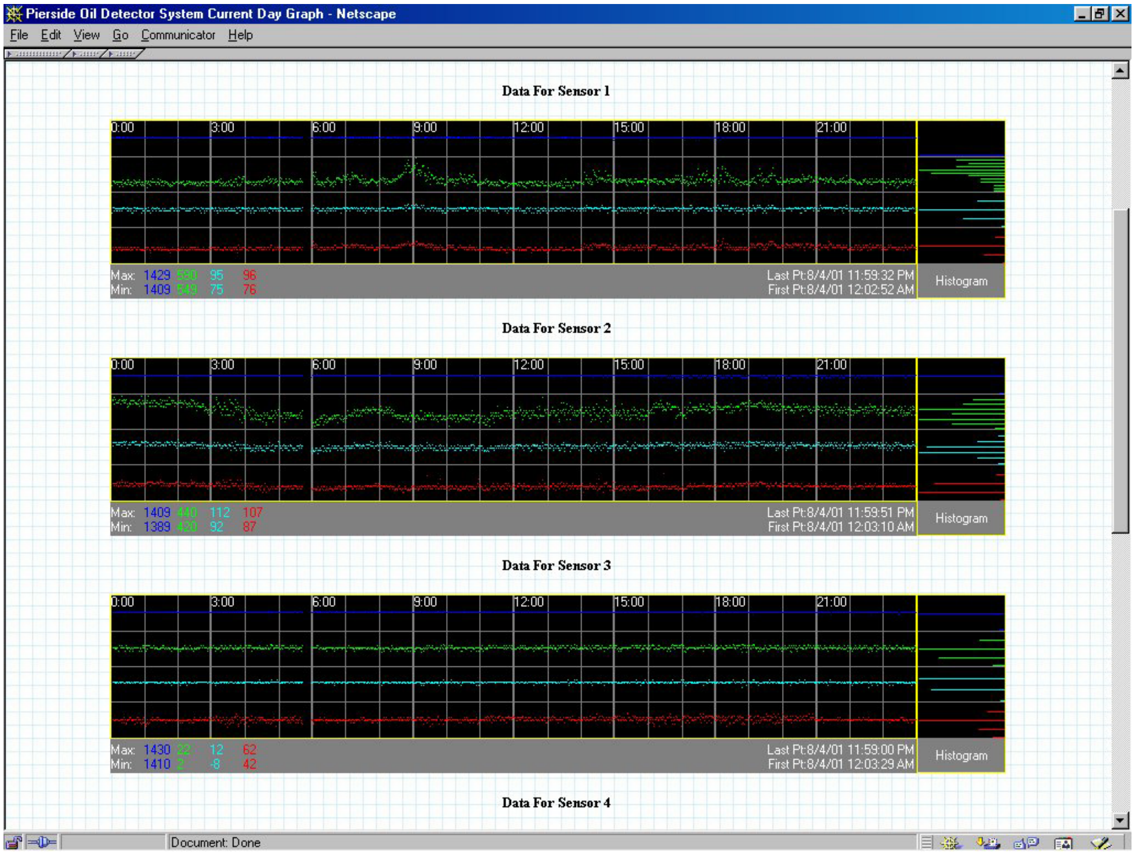


Figure 4.27 User Web Interface: Time Series Charts.

4.3.2.7 <u>Locating</u>

There were no issues with locating the sensors. Sensor placement did not impact local activities at any of the demonstration sites. In most cases, the sensors were simply moored to existing pier structures using half-inch nylon line. Two emplacements, near the Arizona Memorial in Pearl Harbor and at Bousche Creek outfall in Norfolk were anchored. The sensors at PSNS were attached to a vertical cable suspended from the top of the pier and anchored at the bottom by a concrete block. This allowed the sensors to move vertically with the local 16 foot tidal excursions while minimizing horizontal drift.

Sensor deployment did not require any infrastructure modifications were at Pearl Harbor, Langley, or Norfolk. The PSNS installation did require the addition of 2-inch conduit pipe along the length of the pier to support cabling for four hard-wired sensors. The sensors used for the PSNS demonstration were the earliest prototypes and were deployed before the wireless capability was added. Future installations will not require hard-wire connections.

4.3.2.8 Rough Weather

As demonstrated in the Ohmsett tests, the sensors are able to maintain detection capability even in the presence of up to18-inch choppy water, the roughest tested. The sensor performance in this regard exceeded pretest specifications by 50%.

Rough stormy weather was a significant factor in system reliability, though not in the way originally expected. The physical battering of two winter storms caused the loss of three sensors in both Hawaii and Norfolk. The loss was due to inexperience in sensor deployment. The sensors were deployed very close to pier pilings with too much line slack. Lateral motion of the sensor allowed it to contact the pier structure. Under normal circumstances this did not present any problems. However, repeated forceful contact induced by violent storm induced wave action eventually damaged the sensor housings, allowing water to penetrate and destroy the internal electronics. Subsequent installations make use of mooring techniques that limit potential storm damage.

4.3.2.9 Spectral Background Interference

Spectral background interference was not observed during any of the demonstrations. The initial concern was that naturally occurring fluorescent molecules such as chlorophyll would cause false alarms. This was never experienced at any of the sites.

4.3.3 Lessons Learned

The demonstration deployments allowed the opportunity to gain many lessons learned. Most have resulted in modifications or improvements to the spill detection system that makes it a much more reliable system than the one first deployed for these demonstrations. Improvements taken directly from demonstration experiences include:

- Use of a timed auto-reboot to limit base station computer down time
- Use of repeaters and high gain antennas to improve radio communication
- Incorporation of satellite based communication for remote areas
- Protective sensor housing to improve survivability
- Improved mooring and anchoring methods for survivability
- Improved maintenance process involving shipment of damaged sensors
- Easier to interpret user-interface

5.0 COST ASSESSMENT

5.1 COST REPORTING

Table 5.1 shows the system costs that were tracked during the technology demonstrations.

Table 5.1 Tracked Costs, by Category

Direct Environmental Activity Costs		**Indirect Environmental Costs**	**Other Costs and Benefits**
Start-up	**Operation & Maintenance**		
Activity	**Activity**	**Activity**	**Activity**
Capital equipment	Operator labor	Compliance audits	Mission readiness
Equipment modifications	Utilities	Document maintenance	Public image
Site preparation	Consumables (e.g. lamps x 2/yr)	Reporting requirements	Cost avoidance -Liability -Cleanup
Installation	Equipment maintenance		
User training			

Costs were identified separately for each of the four demonstration sites and extrapolated to estimate the average cost of implementation at a new site. There is no existing oil spill detection technology or methodology that costs can be directly compared with; instead a comparison will be made based on the avoided cost due to rapid response.

The direct costs are calculated or defined as follows:

Capital equipment includes durable components that are purchased at start-up including in-water sensors, radio transceivers, antennas, masts, permanent cabling, computer equipment, solar panels and any other major system component or end item.

Equipment modifications includes engineering and material costs necessary to modify the Spill Sentry system to meet local user requirements.

Site preparation covers the cost of any required changes to the local infrastructure to support the Spill Sentry installation. This may include, for example, installation of conduit for cabling, fabrication of mooring support system, or physical modification to a pier.

Installation costs are determined by the number of man hours required for complete system installation including SPAWAR technicians and local user support. When unknown, technician man-hour costs are estimated at $75/hour. This category also includes travel costs and time to the demonstration site from SPAWAR San Diego.

User training cost is estimated as the number of user man hours spent in Spill Sentry meetings or briefings during start-up. When unknown, user man-hour cost is estimated at $75/hour.

SPAWAR does not currently provide a formal user training program for Spill Sentry. Training is provided informally on an as-needed basis.

Operator labor cost is estimated as the number of user man-hours times the labor cost required to maintain or interact with the *Spill Sentry* system during the year.

Utilities represent the cost of electrical power to operate the Spill Sentry system. This typically includes the base station computer, one watt transceiver, and spill sensors if not solar powered. Electricity costs are estimated at $0.10 per kilowatt-hour for each site.

Consumables include non-durable items that require replacement on a yearly basis or sooner. This may include line and hardware for mooring as well as flashlamps and batteries for the sensors.

Equipment maintenance is calculated as the sum of all costs related to maintaining the Spill Sentry system in operable condition. These costs include labor, travel, materials, and equipment usage (e.g. boats).

Indirect costs that were tracked include *compliance audits*, *document maintenance*, and *reporting requirements*. However, reporting requirements are the same with or without the Spill Sentry system. All spills must be reported and there is therefore no impact to cost. Compliance audits were not required at any of the demonstration sites during this study, so again there is no impact to overall cost. Document maintenance is not required per se; however, the modest costs associated with maintaining the sensor data in the base station data base will be included in this category based upon the man-hours dedicated to this purpose.

The *other costs and benefits* category includes items that are very difficult to accurately quantify but nevertheless have a tangible impact to the organization. These include:

Mission readiness. The overall impact to mission readiness during the demonstrations was zero. However, there is a strong potential for the Spill Sentry system to enhance mission readiness by allowing oily waste transfers in port to be performed at night. Current practice generally limits fuel transfers to daylight hours because of the difficulty of visually identifying a spill during darkness. The operational window for these types of activities could double if secure nighttime transfers could be enabled.

Public image. This is another indirect benefit that is difficult to quantify in any meaningfully way. Nevertheless, benefits are very tangible. An example will serve to illustrate the point. During the Spill Sentry sensor installation at PSNS, local news covered the "event," portraying the shipyard as being proactive in its attempts to minimize risk and potential environmental damage to the local waterways. This was the first positive publicity after several years of stories about the real and potential negative ecological impact due to shipyard activities.

Cost avoidance – liability and clean-up. This is the primary cost benefit to automated spill detection. Early response can lead to reduced spill volume and lower clean-up costs. The type of spill event that would derive the most benefit from *Spill Sentry* occurs once every year or two

at most facilities. This is a prolonged spill that begins at night or during the weekend and is not reported for many hours before a response is initiated. During the demonstrations, there were no actual spills of this type detected by the systems. Cost savings in this category will therefore be estimated from spill statistics. It is of interest to note that there was one opportunity to detect a spill at Norfolk within the first weeks after installation. A prolonged spill of at least hundreds of gallons of fuel occurred very near one of the sensors on the weekend before a Presidential visit to the site. The spill was not detected for over 24 hours before a response team was mobilized to clean up the spill. The Spill Sentry system failed in this instance because of high power radio wave interference with the wireless data path. The cause is still unknown but likely due to the use or testing of shipboard radio frequency equipment, perhaps radar, in close proximity to the base station radio antenna. The radio interference problem was resolved during the next maintenance visit but the opportunity was lost.

5.2 COST ANALYSIS

5.2.1 Cost Comparison

The cost of oil spill clean-up in port can vary widely. Factors that influence clean-up costs include:

- Type of product spilled
- Location of the spill
- Timing of the spill
- Size of the spill
- Clean-up techniques employed
- Weather conditions
- Sensitive areas affected
- Local laws and regulations

Etkin[4] sites numerous case studies of oil spills in port with cleanup costs that range from a low of $2.33 per gallon to $1,125.42 per gallon. Two key factors in reducing the impact, and ultimately the cost, of an oil spill in port. First is preparedness, having the appropriate personnel and resources ready to respond. The second is rapid response; it is generally agreed upon that timely response is essential in minimizing cleanup costs.
Filadelfo[5] has analyzed the cost of in-port spills at NAVSTA San Diego and reports similar estimates. Of nine case studies the cost/gallon ranged from a low of $5 to a high of $1,900 per gallon. The mean was $536 / gallon.

The Center for Naval Analysis has identified specific costs associated with Navy Oil spills in port[5]. These include both variable and fixed costs. Variable costs include those expenses directly attributable to a specific spill event and are usually proportional to spill frequency and volume. These would include, for example, labor costs, contract costs, federal and local fines,

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[4] Cleanup Costs for Oil Spills in Ports, Dagmar Schmidt Etkin, *Oil Spill Intelligence Report*, Arlington, MA, 2000

[5] Cost of Navy Oil Spills in San Diego, Jonathon D. Mintz and Ronald J. Filadelfo, Center for Naval Analyses, Alexandria, VA. June 1999.

the value of lost product, and use of consumables. Fixed costs are those that are incurred whether or not a spill occurs; examples include: spill response training, infrastructure costs, and contingency plan preparation.

A cost comparison between the *Spill Sentry* technology and the current method (visual observation) for detecting spills in port must take into account the cost of implementing and maintaining each approach as well as the potential cost savings from reduced clean-up expense. As for implementation and maintenance costs, the currently employed method of visual observation, along with its associated costs, would in all likelihood continue unchanged even if the *Spill Sentry* system were adopted for use. Hence the relative cost of the current method is $0; adoption of Spill Sentry will provide no reduction in the cost of implementing passive visual observation. Any cost benefit from *Spill Sentry* must come from a reduction in clean-up cost relative to system fielding expenses.

It is impossible to estimate the volume of spilled oil that can be avoided by using the *Spill Sentry* system. Statistics are thin and conditions vary greatly. Early detection may have little impact on small spills; *Spill Sentry* will earn its keep by minimizing the volume and impact of large spills, leaking pipes, or overflowing tanks that can be stopped and contained more quickly through immediate detection. But those events occur relatively infrequently. The approach to cost analysis taken here is to estimate the cost of implementing and maintaining a *Spill Sentry* system in comparison to the average or potential cost of a large oil spill. Then, estimate the number or size of an avoided spill(s) necessary to reach a break even point. The potential end user or risk manager can then decide for him or herself whether *Spill Sentry* implementation at their specific location makes economic sense.

5.2.1.1 *Spill Sentry*: One Year Cost Basis for Direct Costs

A breakdown of direct costs for the year long deployments at each of the four demonstration locations is presented below.

Norfolk:

One-Time Start-up Costs	
Capital Equipment:	
Wireless, solar powered spill sensors $12,400 ea x 3 =	$37,200
Base station personal computer (Pentium II)	$ 1,100
Base station radio, radio enclosure, antenna and cable	$ 1,050
Equipment Modifications (none)	$ 0
Site Preparation (Telephone line installed for base station)	$ 200
Installation	
Boat crew	$ 600
Travel to site	$ 2,000
Engineer (20 man hours)	$ 1,700
Navy Technician (E4)	$ 100
User Training	$ 300
Total Start-up Cost	**$44,250**

Annual Operation and Maintenance Costs

Operator Labor	$ 0
Utilities (Base station 250Watts)	$ 219
Consumables (Line, floats, etc)	$ 50
Maintenance (Quarterly)	
Travel x 4	$ 4,000
Engineer (20 man hours) x 4	$ 6,800
Boat Crew (semi annual)	$ 1,200
Total Operation and Maintenance Cost for One Year	**$ 12,269**

Langley:

One-Time Start-up Costs

Capital Equipment:	
Wireless, solar powered spill sensors $12,400ea x 1 =	$ 12,400
Base station personal computer (Pentium II)	$ 1,100
Base station radio, radio enclosure, antenna and cable	$ 910
Equipment Modifications (none)	$ 0
Site Preparation (Telephone jack)	$ 10
Installation	
Travel to site	$ 900
Engineer (10 man hours)	$ 850
Civilian Technician	$ 300
User Training	$ 150
Total Start-up Cost	**$ 16,480**

Annual Operation and Maintenance Costs

Operator Labor	$ 0
Utilities (Base station 250Watts)	$ 219
Consumables (Line, floats, etc)	$ 10
Maintenance (Quarterly)	
Travel x 4	$ 3,600
Engineer (4 man hours) x 4	$ 1,360
Total Operation and Maintenance Cost for One Year	**$ 3,965**

Pearl Harbor:

One-Time Start-up Costs

Capital Equipment:	
Wireless, solar powered spill sensors $12,400ea x 4 =	$ 49,600
Base station personal computer (Pentium II)	$ 1,100
Base station radio, radio enclosure, antenna and cable	$ 2,150
Equipment Modifications (none)	$ 0
Site Preparation (mooring for Arizona location)	$ 200
Installation	

Boat crew	$ 600
Travel to site	$ 2,000
Engineer (30 man hours)	$ 2,550
User Training	$ 300
Total Start-up Cost	**$ 56,560**

<u>**Annual Operation and Maintenance Costs**</u>

Operator Labor	$ 0
Utilities (Base station 250Watts)	$ 219
Consumables (Line, floats, etc)	$ 100
Maintenance (Quarterly)	
Travel x 4	$ 6,000
Engineer (16 man hours) x 4	$ 5,440
Boat Crew (semi annual)	$ 1,200
Total Operation and Maintenance Cost for One Year	**$ 12,959**

Puget Sound Naval Shipyard:

<u>**One-Time Start-up Costs**</u>

Capital Equipment:	
Wireless, solar powered spill sensors $9,600ea x 4 =	$ 38,400
Base station personal computer (Pentium II)	$ 1,100
Base station radio, radio enclosure, antenna and cable	$ 1,550
Equipment Modifications (Pier side transceiver)	$ 1,750
Site Preparation (Enclosures and conduit)	$ 45,000
Installation	
Boat crew	$ 100
Travel to site	$ 1,200
Engineer (20 man hours)	$ 1,700
User Training	$ 1,000
Total Start-up Cost	**$ 93,800**

<u>**Annual Operation and Maintenance Costs**</u>

Operator Labor	$ 0
Utilities (Base station, sensors)	$ 225
Consumables (Line, floats, etc)	$ 150
Maintenance (Quarterly)	
Travel x 4	$ 2,400
Engineer (20 man hours) x 4	$ 6,800
Boat Crew	$ 400
Total Operation and Maintenance Cost for One Year	**$ 9,975**

5.2.2 Cost Drivers

System costs scale closely with the total number of sensors installed at a given location. At an estimated cost of $12K each, the in-water sensors represent the bulk of the system start-up cost. Operation and maintenance costs would also increase in proportion to the number of installed sensors.

5.2.3 Life Cycle Costs

Anticipated *Spill Sentry* life cycle costs can be estimated from the demonstration deployment expenditures. Operation and maintenance costs are estimated to be somewhat lower than experienced during the demonstrations because the sensors will in most cases be serviced locally or, when necessary, shipped for repair; hence significantly smaller travel costs will be involved. The start-up costs can be expected to be similar to the demonstration costs for wireless system installations. The time period for calculating the life cycle cost is obviously a critical part of the calculation. A conservative estimate of a five year service life for the system will be used for this example. After five years the computer base station may need to be updated, an estimated one half of the in-water sensors at a given site may have been damaged beyond repair due to storms or other mishap. The radio systems, a small fraction of the total system cost will probably still have several years of useful service remaining after five years. This example will be based on a four sensor wireless installation. The future value of money is ignored for these calculations.

The facility capital cost, site modifications necessary to accommodate Spill Sentry implementation will vary but might typically include installation of a phone line along with installation of an Ethernet hook-up if neither are already available for the base station computer. Estimated cost: $200.

Startup costs can be estimated directly from the start-up costs associated with the four-sensor installation performed for Pearl Harbor demonstration. Estimated cost: $56,600.

Operations and maintenance costs over the five year life will be estimated assuming 2 sensor repairs per year, annual lamp and battery replacement for each sensor, and two man-hours per sensor per month maintenance and cleaning. Labor costs are estimated at $40/hr. The use of a boat crew is added in assuming twice yearly use, two hours each time.

Operator Labor (60 mo. x 8 hours/mo. x $40/hr)	$ 19,200
Utilities (Base station 250Watts)	$ 1,095
Consumables (Line, floats, etc)	$ 250
Sensor repair ((2/yr. at $300 each case)	$ 3,000
Routine maintenance (parts, $400/sensor/yr.)	$ 8,000
Boat Crew (semi annual)	$ 4,000
Total Five-Year Operation and Maintenance Cost	**$ 35,545**

Demobilization costs are limited to the labor expense of removing the in-water sensors and base station computer. This is estimated to take 5 hours at a total cost of $200.

Equipment replacement costs can be estimated by assuming that one additional in-water sensor is purchased to either replace a failed unit or temporarily replace units that are being sent off for repair. The cost for one solar powered wireless *Spill Sentry* sensor is $12,400.

Future environmental compliance liability is zero, (the technology does not create or store a contaminant).

The total five life cycle cost is estimated as the sum of the individual costs listed above. This cost is tabulated in Table 5.2.

Table 5.2 *Spill Sentry* Five-year Life Cycle cost

Item	Cost
Facility capital cost	$ 200
Start-up cost	$ 56,600
Operation and maintenance cost	$ 35,545
Demobilization cost	$ 200
Equipment replacement cost	$ 12,400
Total five-year life cycle cost	**$104,945**

5.3 COST ANALYSIS

The potential cost avoidance provided by the *Spill Sentry* system would come by way of: a reduction in federal, state, and local fines including National Resource Damage Assessments (NRDA), avoided loss of petroleum, lower cleanup costs (rapid response), ability to conduct 24 hour port operations, and perhaps even a reduction in the cost of having a required visual watch.

In terms of spill prevention (minimization), the Spill Sentry system could pay for itself by reducing the volume of a single spill by as little as 200 gallons. Using the average cleanup cost of $536/gallon cited above along with the five-year *Spill Sentry* cost estimate of nearly $105,000.00, the system could pay for itself by preventing 196 gallons from accidentally being released into the environment over its five-year service life.

6.0 IMPLEMENTATION ISSUES

6.1 ENVIRONMENTAL CHECKLIST

No permits are required to install and use the *Spill Sentry* system. The system does not generate any hazardous waste. The one-watt radio transmitter used in wireless versions of the *Spill Sentry* sensor does not require an FCC license. The system can be installed and used without the need of any local permitting or regulatory approval.

6.2 OTHER REGULATORY ISSUES

In California, the California State Lands Commission is considering making a formal endorsement of the *Spill Sentry* system and currently recommends it to waterfront managers. It is possible that the Lands Commission may mandate the use of the *Spill Sentry* or similar systems at all waterfront facilities at an unspecified future date as a way of enforcing the Lempert-Keene-Seastrand Oil Spill Prevention and Response Act of 1990.

6.3 TRANSITION

The *Spill Sentry* oil spill detection technology was transitioned to the private sector during the first year of the ESTCP validation effort. The sensors used in the Norfolk, Langley and Hawaii deployments were in fact early production prototypes manufactured by commercial transition partner Applied Microsystems Ltd. (AML, Sidney, B.C.). The U.S. Navy assigned exclusive rights to manufacture and market the Spill Sentry technology to AML in exchange for an initial licensing fee and royalties on all future sales of *Spill Sentry* systems worldwide. In addition, the U.S. federal government receives discounted pricing for *Spill Sentry* systems purchased for government use and activities. AML has sold *Spill Sentry* systems worldwide and continues to manufacture and market the systems. Additional information on the AML *Spill Sentry* can be found on the Internet at:

http://www.appliedmicrosystems.com/sensors/oil-on-water.html

The SPAWARSYSCEN *Spill Sentry* technology transfer effort has led to receipt of the *Federal Laboratory Consortium* 2001 Award for Excellence in Technology Transfer.

In addition to the commercial transition, the *Spill Sentry* oil spill detection system has been adapted to other military and commercial uses by incorporating additional sensing technology onto the sensor platform. A modified version the *Spill Sentry* has recently been deployed in the Persian Gulf by the U.S. Navy Meteorological and Oceanographic Command for collecting bioluminescence and optical transmission data as well as oil spill (fluorescence) data in Manama Harbor, Bahrain. Other DoD agencies have also purchased modified sensors for military applications.

Figure 6.1 AML *Spill Sentry* Advertisement.

6.4 END-USER ISSUES

End users can now obtain *Spill Sentry* systems, system service, and support directly through AML. The technology currently being marketed by AML has benefited significantly from the lessons learned from the ESTCP demonstrations. The newest generation of sensors has been improved to be more durable, safer and easier to deploy. Nevertheless several user concerns still remain, including concern about system sensor ruggedness and survivability, particularly during storms, and false positive alarming. Additional planned demonstrations, system deployments undertaken by early adopters, and the incorporation of evolutionary engineering improvements will eventually provide the basis and track record for mainstream users to decide whether or not to employ automated spill detection at their local facility.

Figure 6.2 Modified *Spill Sentry* in Manama Harbor.

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7.0 REFERENCES

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8.0 POINTS OF CONTACT

Table 8.1 Points of Contact

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